JOINT PAINT REMOVAL STUDY

JOINT POLICY COORDINATING GROUP ON DEPOT MAINTENANCE

TASKING DIRECTIVE 1-90

FINAL REPORT

ON

LASER PAINT REMOVAL

FOREWORD

This report is the last of five individual studies directed by the Joint Policy Coordinating Group on Depot Maintenance in Tasking Directive 1-90 (Appendix I). The focus is on the Navy's contract for the Automated Laser Paint Stripping (ALPS) system. The contract was for testing to prove the feasibility and developing a robotic-controlled laser that could remove paint from aircraft exterior surfaces. This report provides the evaluation test plan, test results, and a description of the major subsystems of the Navy ALPS. It also identifies and describes the Air Force and Army's limited-or special-purpose laser strippers.

The points of contact for the Joint Paint Removal Study are at Appendix III.

EXECUTIVE SUMMARY

BACKGROUND:

The Joint Policy Coordinating Group on Depot Maintenance (JPCG-DM) tasked the Joint Technology Exchange Group (JTEG) to study alternative paint removal processes that have potential use within the Department of Defense (DOD) depot maintenance community. The JPCG-DM signed Tasking Directive 1-90 on 19 Dec 89 (Appendix I). The JTEG was directed to plan and manage the study, identify techniques to stud, sponsor and advocate research and development initiatives, oversee joint Service testing, evaluate the study, and report the results.

OBJECTIVE:

The objective of the study is to give managers coordinated joint Service technical and management information to help them make investment and application decisions regarding current and emerging paint removal processes. The study will identify and evaluate alternative paint removal processes and help managers eliminate duplicate developmental efforts.

SCOPE:

To realize the quickest benefits, the scope of the JTEG's study was limited to five paint removal processes: plastic media blasting, sodium bicarbonate blasting, carbon dioxide pellet blasting, high-pressure waster blasting, and laser. To reduce costs and time frames, facilities that had already established or begun efforts to establish organic capabilities for a particular technology conducted the tests.

STUDY PLAN:

Phase I was a comprehensive review, within DOD, to identify existing capabilities or plans and to establish a baseline for the study. The baseline, which related to the five paint removal processes, identified current capabilities, the degree of maturity for each paint removal method, developmental efforts and time frames, and study criteria. Also, from the baseline data, lead activities were recommended and study teams established.

Phase II was the feasibility study, testing, and analysis phase, which began by designating lead activities and developing a coordinated plan for each process to include economic, environmental, and technical evaluations. During Phase II, the JTEG periodically reported the status of each process to the JPCG-DM and the depot maintenance community.

Phase m involved analyzing and documenting the processes. Final reports were provided for each process. Following the completion of all individual studies, a report will be provided to the JPCG-DM to close Tasking Directive 1-90.

SUMMARY:

Although laser paint strippers are being used in limited applications, laser stripping is still considered an emerging technology. All key technologies needed to build laser stripping systems are available and have been demonstrated. The questions that remain relate to the control process that ensures repeatable, non-damaging removal. The systems in use are designed to control the laser and eliminate the need for precision robotics.

Naval Air Systems Command initiated an advanced technology contract with International Technology Associates (InTA), Santa Clara, CA, in 1989. The Navy contracted a group of validation tests (phase 1) to document the feasibility of using a laser to strip paint and the development of an Automated Laser Paint Stripper (ALPS) to strip a fighter-size aircraft.

Phase I of the ALPS contract was divided into two tasks (Ia and Ib). Test results of phase Ia were generally positive, but the Navy identified areas of concern and subsequently had supplemental tests performed. There were also concerns about possible overheating of composite substrates to be tested in phase Ib. As the test program proceeded, the Navy approved the initiation of phase II (design). Then in 1993 the Navy asked InTA for a cost estimate for conducting the final phase of testing. The estimate exceeded the available funds remaining on the contract. A pre-termination conference was held at Naval Air Systems Command and the Navy's principals agreed to terminate the contract for convenience of the government. They wanted another contractor to continue the test program with the remaining funds but, by regulation, the funds could not be reallocated.

The Air Force and Army reviewed the Navy's phase Ia, Ia-supplemental, and lb test results to support investment decisions for procuring limited- or special-purpose laser strippers.

The Air Force's decoating system is a turn-key procurement from BDM Federal Inc., Albuquerque, NM. The system uses a high-energy CO: pulsed laser to remove rain erosion coatings from composite aircraft radomes and flight control surfaces.

The Army's decoating system is a turn-key procurement from Silicon ALPS, Santa Clara, CA. The system uses a high-energy CO: pulsed laser with real-time vision feedback control to remove coatings from medium to large components. The system was procured specifically for stripping helicopter rotor blades.

Laser paint stripping is still in its infancy; however, the technology is proven to be easily adaptable to different paint systems and substrates. It is the only known efficient method of stripping that generates less disposable waste than the initial volume of paint applied.

TABLE OF CONTENTS

			PAGE
FOREWORD			I
EXECUTIVE SUMMARY			ii
TABLE OF CONTENTS			iv
SECTION 1 – OVERVIEW OF LASER PAINT STRIPPING			1
1.1 INTRODUCTION			1
1.2 APPLICATIONS			2
1.3 GENERAL DESCRIPTION OF LASER PAINT STRIPPING			2
SECTION II – AUTOMATED LASER PAINT STRIPPING PROGRAMS			4
2.1 NAVY AUTOMATED LASER PAINT STRIPPER (ALPS)			4
2.2 AIR FORCE AUTOMATED DEPAINTING SYSTEM (LADS)			5
2.3 ARMY AUTOMATED LASER PAINT STRIPPER (ALPS)			6
SECTION III – LASER STRIPPING SYSTEMS DESCRIPTION			7
3.1 NAVY ALPS			7
3.2 AIR FORCE LADS			10
3.3 ARMY ALPS			13
SECTION IV – TEST PROCEDURES AND PRACTICES			15
4.1 NAVY ALPS PROGRAM			15
	4.1.1	Program phases	15
	4.1.2	Phase Ia test procedures description	15
		4.1.2.1 Aircraft substrates tested	15
		4.1.2.2 Pre-treatment and coating	15
		4.1.2.3 Controls	15
		4.1.2.4 Overexposed strip cycle	16
		4.1.2.5 One strip cycle	16
		4.1.2.6 Parametric study	16
	4.1.3	Phase I1 test results	17
		4.1.3.1 Surface changes after stripping	17
		4.1.3.2 Differences between anodize layers	17
		4.1.3.3 Scratch tests	17
		4.1.3.4 Mechanical tests	17
		4.1.3.5 Composite samples overexposed	17
		4.1.3.6 Metallic specimens	17
		4.1.3.7 Stripping patterns and parameters	18
		4.1.3.8 Visual inspection	18
		4.1.3.9 Stereo microscopic inspection	20
		4.1.3.10 Surface roughness tests	20
		4.1.3.11 Conductivity testing	21
		4.1.3.12 SEM surface analysis	22
		4.1.3.13 Metallographic cross sectioning	23
		4.1.3.14 Tensile testing	24
		4.1.3.15 Parametric study	25

	4.1.4	Phase Ia conclusions	26
	4.1.5	Phase Ia recommendations	27
	4.1.6	Phase Ia supplemental test plan	27
	4.1.7	Phase Ia supplemental test results	29
		4.1.7.1 Post-strip analysis of anodize coating	29
		4.1.7.2 Tensile testing	30
		4.1.7.3 Temperature rise testing	31
	4.1.8	Phase Ia supplemental conclusions	33
	4.1.9	Phase Ia supplemental recommendations	34
	4.1.10	Phase Ib test plan	34
	4.1.11	Phase Ib test implementation	35
		4.1.11.1 Paddle testing	35
		4.1.11.2 Panel testing – constant PRF	36
		4.1.11.3 Panel testing – varying PRF	37
		4.1.11.4 Metallographic set-up	37
	4.1.12	Phase Ib results	38
		4.1.12.1 Graphite epoxy paddle temperature rise testing	38
		4.1.12.2 Graphite epoxy panel paint stripping	38
		4.1.12.3 Fiberglass panel paint stripping	39
		4.1.12.4 Metallographic examination	40
	4.1.13	Phase Ib tests conclusions	40
	4.1.14	Phase Ib recommendations	41
4.2	AIR FORCE LADS PROGRAM		41
	4.2.1	LADS procurement	41
	4.2.2	Coat removal scenario	42
	4.2.3	Summary of F-4 and F-16 radome strip tests	44
	4.2.4	Conclusions	45
4.3	ARMY ALPS		45

			PAGE
APPENDIX I		JPCG-DM TASKING DIRECTIVE	I-1
APPENDIX II		TABLES	II-1
	TABLE 1	ALPS Phase Ia Test Matrix	II-1
	TABLE 2	Pre-painting Surface Roughness Measurements	II-3
	TABLE 3	Post-stripping Surface Roughness Measurements	II-3
	TABLE 4	Conductivity Measurements	II-4
	TABLE 5	Metallographic Cross Section Thickness Results	II-4
	TABLE 6	Static Tensile Properties (Control and Overexposure) of 1A-200 and 1A-300 Specimen	II-5
	TABLE 7	Static Tensile Properties (Control and Overexposure) of 1A-100 Specimen	II-6
	TABLE 8	ALPS Phase Ia Supplemental Test Matrix	II-7
	TABLE 9	Average Roughness Measurements in Microinches	II-8
	TABLE 10	Tensile Test Results, Clad 7-75-T6	II-9
	TABLE 11	Tensile Test Results, Clad 2024-T3	II-11
	TABLE 12	Tesnsile Test Results, Bare 2024-T3	II-13
	TABLE 13	Aluminum Temperature Rise Above Ambient for Single Strip (approximately 14 pulses) 1A-200 and 1A-300 Specimen	II-15
	TABLE 14	Sample Numbers for Phase Ib Single Strip and Four Cycle Testing	II-16
	TABLE 15	Paddle Sample Thickness and Depth of Thermocouple Near the Front Surface	II-17
	TABLE 16	Paddle Sample Test Parameters and Results	II-17
	TABLE 17	Polyurethane Coated Epoxy (Sample B58) Rear Surface Temperature Rise Measurements and Peak Temperature Estimates for 0.002 inch Below the Front Surface	II-18
	TABLE 18	Rain Erosion Coated Epoxy (Sample B59) strip Parameters, Rear Surface Temperature Rise Measurements and Peak Temperature Estimates for 0.002 in Below the Front Surface	II-19
	TABLE 19	Walkway Coated Graphite Epoxy (Sample B60) Strip Parameters, Rear Surface Temperature Rise Measurements and Peak Temperature Estimates for 0.002 inch Below the Front Surface	II-20
	TABLE 20	Polyurethane Coated Fiberglass (Sample B49) Strip Parameters, and Rear Surface Temperature Rise Measurements	II-20
	TABLE 21	Strip Parameters and Rear Surface Temperature Rise Measurements for the Second Set of Polyurethane Coated Fiberglass Samples	II-21
	TABLE 22	Four-point Flexure Test Results Summary for Graphite Epoxy Samples	II-21
	TABLE 23	Four-point Flexure Results	II-22

	TABLE 24	Four-point Flexure Test Summary for Fiberglass Samples	II-24
	TABLE 25	Four-point Flexure Test Results for Unpainted Fiberglass	II-25
	TABLE 26	Four-point Flexure Testing of Fiberglass (Anamet Laboratories, Inc.)	II-27
APPENDIX III		Points of Contact for the Joint Paint Removal Study	III-1

SECTION I - OVERVIEW OF LASER STRIPPING

1.1 INTRODUCTION

1.1.1 Laser paint stripping is a non-intrusive and low-kinetic energy ablating process that requires a minimum of surface preparation and post process activities. At the onset of the laser paint removal developmental effort it was known that the laser was efficient at removing paint and that the disposable waste generated by the process is less than the initial volume of paint applied. Safety is a major concern for equipment design and integration.

1.1.2 Current chemical or mechanical paint stripping practices involve the use of hazardous materials, which results in numerous personnel health and safety procedures. Just as important are the volatile and liquid effluents, which significantly contribute to polluting the environment. Severe restrictions on the use of most of the hazardous materials involved, and outright banning of some, are either already in place or are scheduled to be by the turn of the century. Complying with imposed restrictions translates directly to high costs and increased time.

1.1.3 Avoiding exposure of operators and surrounding personnel and capturing and treating effluents from operations before disposal necessitate significant developments with the risk that developmental efforts may not produce satisfactory solutions. However, failure to succeed in avoiding the exposure of operators and surrounding personnel or in avoiding pollution could translate into higher costs due to legal liabilities.

1.1.4 Important operational issues related to damage of the substrate must be answered before an alternative to chemical or mechanical paint stripping is accepted. The development and implementation of a paint stripping operation based on lasers and intelligent robotics addresses the principal issues that constrain chemical and mechanical paint stripping operations. The attributes of laser stripping are that the process:

- eliminates the use of toxins and large volumes of hazardous waste. The small volume of particulate from the coatings and paints, even if hazardous, can be handled easily.

- eliminates potential failures initiated by corrosion caused by chemical residues in faying surfaces and seams.

- contains and potentially reduces the cost and time of paint stripping operations. Higher costs anticipated with future chemical and mechanical operations would not be exceeded. In addition, considering intelligent automation, laser stripping may be less costly and more reproducible than chemical or mechanical stripping.

- avoids operator-dependent accidental damage to substrates by using automated robotics operations.

1.1.5 The objective of the Navy's validation tests was to make sure that deficiencies associated with substrate heating and subsystem integration were resolved. Process evaluation- tests conducted for the Navy were to determine the optimum operating parameters for applying a minimum of directed energy to achieve damage-free results and to optimize paint removal rates.

1.2 APPLICATIONS.

1.2.1 The Navy contract for the Automated Laser Paint Stripper (ALPS) was with International Technical Associates (InTA), Santa Clara, CA. InTA was to develop an automated, cost effective, environmentally sound, and safe system for stripping fighter-size aircraft. Two systems were to be delivered. One system was to be installed at Naval Aviation Depot (NADEP) Cherry Point, NC and the other at NADEP Norfolk, VA. InTA was granted a patent for their control system in May 1986 that uses a concept of real time vision feedback for control. The control system not only controls the paint removal process, but also eliminates the need for precision robotics.

1.2.2 The Air Force contract for the Laser Automated Decoating System (LADS) was with BDM Federal Inc., Albuquerque, NM. The Ogden Air Logistics Center (OO-ALC) in cooperation with the Aeronautical Systems Center’s Reliability, Availability, and Maintainability Technology Insertion Program (RAMTIP) office awarded BDM a task to (1) validate the feasibility of using a high energy CO2 pulsed laser to remove rain erosion coatings from composite aircraft radomes and flight control surfaces, and (2) develop a system to remove coatings from F-16 radomes. Plasmatronics Inc., the principal subcontractor, developed a 1200-watt pulsed laser subsystem that generates a square laser beam of about two square centimeters with a Raleigh range of about 18 inches. The resulting beam qualities ablate coatings without crating excessive heat or without the potential for creating surface grooves. This, in turn, simplified the development of the robotics and integration of the total system.

1.2.3 The Army contract for an automated laser paid stripping cell was with Silicon ALPS Corporation, Santa Clara, CA. Corpus Christi Army Depot's (CCAD) procured a turn-key system, model LS4000, which is designed to handle medium to large components, employing both a robot arm and rotational parts positioner. The system was procured specifically for stripping helicopter rotor blades.

1.3.1 The operative word for describing laser paint removal is removal by "ablation". By definition, to "ablate" is to remove by cutting, eroding, melting, evaporating, or vaporizing. A beam of laser energy striking a surface volatilizes the surface coating.

1.3 GENERAL DESCRIPTION OF LASER PAINT STRIPPING.

1.3.2 After a thorough investigation for the optimum application, InTA found that pulsed laser radiation with a relatively low peak power was the most effective and controllable means of using laser technology to remove paint. Using this concept, a small quantity of coating is removed with each pulse and the target area is allowed to cool before being processed again. Continuous wave (CW) radiation raises the surface to such a high temperature that the remaining coating is changed. Pulsed lasers with high peak power ratings produce a plasma at the surface that produces plasma detonation waves in the material they are removing. Best results are obtained by rastering the laser pulse. That is, after each area receives a pulse, move to a new area rather than working on just one area to remove all paint. The laser energy, pulse duration and power, does not vary during the paint removal process and, by design, each pulse removes only a small quantity of paint.

1.3.3 The feedback control system developed by InTA and a rastering technique removes the requirement for precision robotics. The decision to pulse the laser at a given location to remove some of the coating is made by comparing or matching the surface color to a set of parameters stored in a computer. A spectrograph is used to examine the color of the surface. The spectrograph can divide light from the coating area into 128 different colors ranging from near ultraviolet to near infrared and cover all visible colors. The spectrum of colors stored in the computer for removal is compared to the spectrum of the surface. If they match, the laser is pulsed. The process continues until the colors no longer match.

SECI'ION II - AUTOMATED LASER PAINT STRIPPING PROGRAMS

2.1 NAVY AUTOMATED LASER PAINT STRIPPER (ALPS) PROGRAM.

2.1.1 Naval Air Systems Command initiated its contract with InTA in 1989 for development of a robotics controlled laser which could be used to remove paint from fighter-sized aircraft. The turn-key system proposed by InTA featured a patented end effector concept with real-time vision feedback control. Waste management, safety, and reliability was to be emphasized in the design and the system would be flexible and easily adapted to new aircraft, paint systems and substrates (both metallic and composite). In Jan 1990 the program was planned in four phases:

2.1.1.1 Phase I tasks:

- application lab implementation
- parametric study
- test panel evaluation
- laser system long-lead development
- integration of Army and Air Force testing
- phase I design review

2.1.1.2 Phase II tasks:

- systems design, engineering, and development
- laser system long-lead development
- systems design review

2.1.1.3 Phase III tasks:

- hardware development
- preliminary acceptance testing

2.1.1.4 Phase IV tasks:

- systems shipment

- installation
- training
- testing
- final acceptance tests

2.1.2 InTA's validation testing, phase L was divided into two tasks, phase Ia and phase lb. Phase Ia was to verify that the laser paint stripper was suitable for depainting military aircraft by stripping and analyzing a small sampling of substrates/coatings. Phase lb, to be initiated after Ia tests were reviewed and approved, would include 3779 tests on a larger matrix of substrates and coatings. In Feb 91 phase Ia was completed and, although the results were generally positive, phase Ia supplemental tests were initiated. Phase Ia supplemental tests repeated the temperature rise and tensile tests, and the laser optics were adjusted to achieve better results in eliminating anomalies exhibited when sulfuric acid anodize is exposed to laser light.

2.1.3 The validation tests would be used to calculate coating removal rate, condition of the remaining paint, condition of the substrate, and other criteria InTA's approach was tested on a number of coatings and substrates:

2.1.3.1 Coatings:

- black polyurethane paint
- white polyurethane paint
- white polyurethane paint aged 5 years
- gray polyurethane paint
- green epoxy primer
- green CARC (chemical agent resistant coating) paint
- gray walkway (silicon carbide grit in epoxy matrix
- white urethane film (3M pressure sensitive adhesive backed decals)
- clear printed circuit board conformity coating
- white rain erosion coating
- gray plessey radar absorbing material, type 9641A

- gray plessey radar absorbing material, type ERAP
- ray plessey radar absorbing material, type neoprene VIMI(1)-5

2.1.3.2 Substrates:

- anodized aluminum
- graphite epoxy composite
- isographite epoxy composite (fiber IMG, matrix 3501-6)
- glass reinforced plastic
- boron epoxy composite
- G-10 printed circuit board composite

2.2 AIR FORCE LASER AUTOMATED DECOATING SYSTEM (LADS) PROGRAM.

2.2.1 The Ogden Air Logistics Center initiated its contract with BDM Federal Inc., Albuquerque, NM, in Oct 91. BDM began with a requirements definition study and tested and analyzed numerous diverse and significant coat removal jobs theoretically. The preliminary design phase began in Jan 92 and was completed in May 92. The final design was completed in Oct 92 with the development of a high-energy pulsed laser to meet the parameters identified in the requirements study. A totally unique laser had to be developed to meet the requirements.

2.2.2 The technology developed by Plasmatronics, Inc., resulted in the generation of a square laser beam of about two square centimeters with a Raleigh range of about 18 inches. The resulting beam qualities ablate the coatings without creating undo heat or without the potential for creating surface grooves as might be done by a more narrowly focused beam. This in turn simplified the development of the robotics and the integration of the total system.

2.2.3 The Air Force's procurement was for a turn-key operational system. The contractor as the overall LADS system integrator, designed, built, and tested the individual subsystems. The contractor also directed the facility work at Hill AFB.

2.2.4 LADS was developed to solve a series of problems that were being encountered in the refurbishment of F-16 radomes. The principal objective was to improve the quality of production that can be achieved with the chemical stripping process in removing the fluoroelastomer, rain erosion coatings from radomes. Chemical stripping required considerable scrapping and sanding, and then the radomes had to be passed to a subsequent process. There was a high degree of variability in this radome refurbishment process. Many radomes could not be cleaned to a usable level and were subsequently scrapped. During the first month of LADS operation seven radomes that had been scrapped were reclaimed. At $36,000 each, this is a savings of over $250,000.

2.3 ARMY AUTOMATED LASER PAINT STRIPPER (ALPS) PROGRAM.

2.3.1 The Corpus Christi Army Depot (CCAD) initiated its contract with Silicon Alps, Santa Clara, CA, in Oct 94. Silicon Alps, a satellite of InTA, was formed specifically to commercialize on the technologies developed by InTA. Silicon Alps, like its parent InTA, specializes in systems integration. The Army's Automated Laser Paint Stopper (ALPS) was delivered to CCAD in Jan 96.

2.3.2 The Army's procurement was for a turn-key operational system. The ALPS underwent preliminary acceptance testing at the contractors facility in mid-December, 95, and passed critical test parameters to the Army's satisfaction. ALPS was delivered to CCAD in Jan 96, and retesting was required only for cements of the system's control software.

SECTION III - LASER STRIPPING SYSIBMS DESCRIPTIONS

3.1 NAVY ALPS SYSTEM.

3.1.1 From a detailed analysis of fighter sized aircraft configurations, substrates, and coating schemes, InTA in conjunction with the Navy determined the system design requirements. The system must be:

- able to strip 3-5 ft^2 / minute.
- able to strip coatings from both metals and composites without degrading substrates.
- maneuverable and able to access the major areas of an F-14, F-18, AV-8B, F4, A-6, and other rotary winged aircraft.
- capable of controlling contaminants that emanate from the process.
- outfitted with safety systems/interlocks for both perimeter and cell safety.

3.1.2 The cell, figure 1, which was conceived to satisfy the above requirements, consists of the following eight major elements:

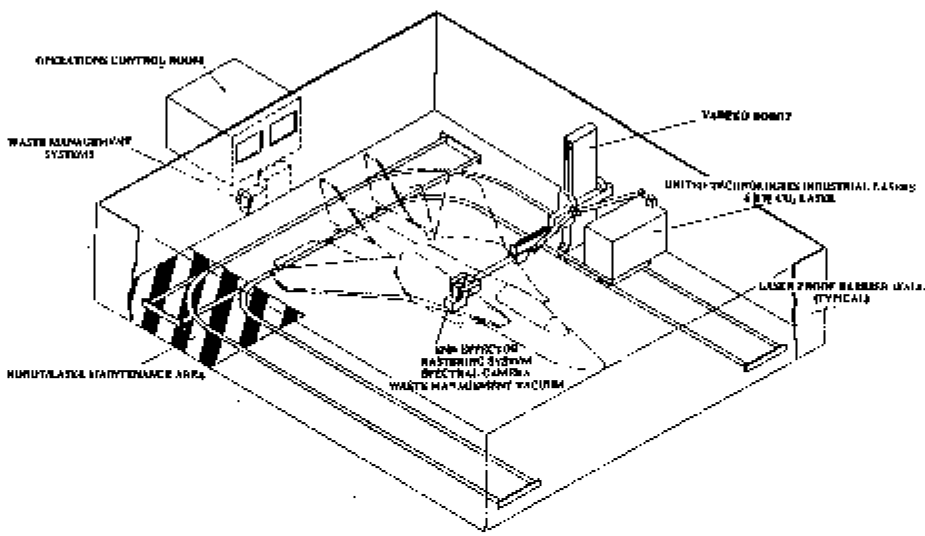

Figure 1. - Cell Layout

3.1.2.1 Laser. InTA chose United Technologies Industrial Laser Division to develop a laser that would meet the performance requirements. InTA's investigations indicated that pulsed CO2 laser radiation with a peak power of 200-300 KW/cm2 would be optimum. To achieve the required power density on a square shaped pulse of 1.1 cm on a side, requires a 30-l microsecond-long, 6-joule pulse. The laser performance requirements to remove between 150 and 300 microinches of coating per pulse, depending on the type of coating, are:

- Output power 6 KW
- Pulse repetition frequency 1000 Hz
- Pulse energy 6 J
- Pulse width 30 ps
- Pulse power (peak, averaged over pulse) 300 KW
- Pulse energy repeatability - 5 %
- Pulse timing repeatability 200 ns

3.1.2.2 Robot. The robot is a track mounted, pedestal type with seven degrees of freedom. Vadeko was chosen to supply the robot. The platform mounted system has the capability of reaching all areas of an aircraft and has an added benefit of being able to carry the laser and other subsystems. Because the robot is of modular design, it may be re-configured to address larger aircraft in future applications.

3.1.2.3 Multispectral camera. The spectra of surface colors to be removed are stored in a computer before the stripping process begins. A feed-back loop is necessary for comparing the color of the surface at a given location to the stored spectra before the laser is pulsed. A spectrograph is used to divide light from the surface into different colors for comparison. Colors from the spectrograph can range from near ultraviolet to near infrared, including all visible wavelengths. If the colors from the spectrograph match, the laser is pulsed and a small amount of coating is removed. This process continues until the color no longer matches those stored in the computer.

3.1.2.4 End effector. The end effector housing is 2 ft3 with a flexible hood extending another 18 inches. It houses the rastering system, spectrometer, waste evacuation tube, and the air knife for optics protection. A reconfigurable, flexible hood is attached to the housing to trap the effluents. The effluents are forced into the waste evacuation tube by using a second air knife.

3.1.2.5 Rastering system. Rather than working on one area to remove all the coating, the laser processes a larger area, called a frame, before returning to process any location again. This is called "rastering". The raster pattern in a frame covers a 30- by 30-centimeter area that consists of 30 rows by 30 columns, see figure 2. Rastering allows each area to cool before it is processed again. This is especially important for coatings like sealant or when removing coatings from composite substrates. Once a frame is clean of any color coating whose spectra was stored in the computer, the system commands the robot to move to a new frame. The surface to be stripped is mapped into a series of paths consisting of adjacent frames and to ensure that all of the coating is removed with no lines or bands remain, the frames are overlapped. This negates the need for a precision robot.

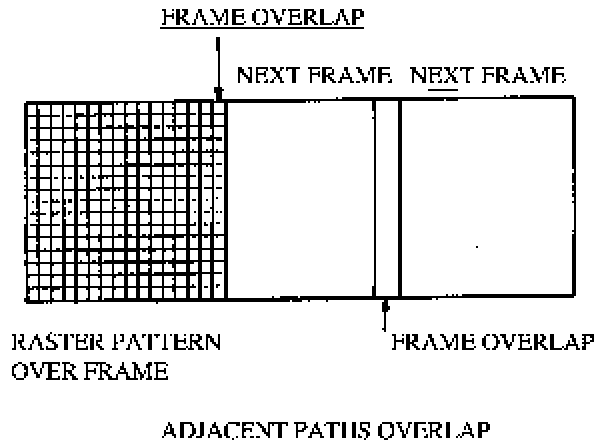

Figure2. Raster Frames

.

3.1.2.6 Waste management system. Material is removed by vacuuming as it is created. It travels through the waste evacuation tube located on the end effector to a waste processor. The waste processor separates the waste into particulate material and vapors. The particulates are filtered out, dried, and placed in storage containers. The vapors are oxidized and converted to carbon dioxide, nitrogen, and water vapor.

3.1.2.7 Cell controller. The workable controller is responsible for the entire operation of the process. The control system is on a VME bus based computer with a real-time UNIX operating system. Multitasking and multiprocessor UNIX capability allow control of thc VO system and the laser safety system. The operator interface computer and simulation workstation are in the control room and the real-time computers are located inside the workcell on a cart.

3.1.2.8 Safety system. The safety system provides a class 1 1aser enclosure which ensures both personnel and facility safety. The principal hazards are those associated with the robot, movement of aircraft into and out of the workcell, and the high powered laser. The system operates automatically under the supervision of an operator in a control booth overlooking the work area The operator is never exposed to risk during the operation. The greatest risk to personnel, equipment, and facilities occurs during servicing and maintenance; however, numerous safety features are incorporated in the work cell to mitigate these risks. Emergency stop switches establish laser, robot motion, and high-voltage safety. They do not depend on normal functioning of logic shutdown circuits. The emergency stop switches are located on each side of the aircraft entry door, adjacent to every personnel exit door, along all walls at no more than 20-foot intervals, and on the operator's console. The switches are wired in series to form two independent series chains, one for laser interlocking and one for the robot. The laser interlock chains disable AC line power to laser high voltage power supplies, and the robot interlock chain disables line power to the robot servo amplifiers. Control computer power is not affected by the emergency stop interlock switches. The laser high-voltage capacitors are discharged within 10 seconds after the activation of an emergency switch.

3.2 AIR FORCE LADS SYSTEM.

3.2.1 The Laser Automated Decoating System (LADS) was developed, fabricated, integrated, tested, and installed by BDM Federal Inc. at Hill AFB, UT, to replace the chemical coating removal processes used in the radome repair/refurbishment shop. The LADS capability improved the reliability and maintainability in the radome refurbishment processes, reduced labor costs, and reduced the levels of hazardous waste generated by the chemical processes. LADS is expected to remove coatings at a rate of 200 square feet per mil thickness of coating, per hour.

3.2.2 The overall LADS facility consists of three rooms, figure 3. These are the laser room where the laser beam is generated; the process room, where the coating is removed from the F-16 radome, or other component; and, the control room, where the operator observes and controls the process. There are six major subsystems:

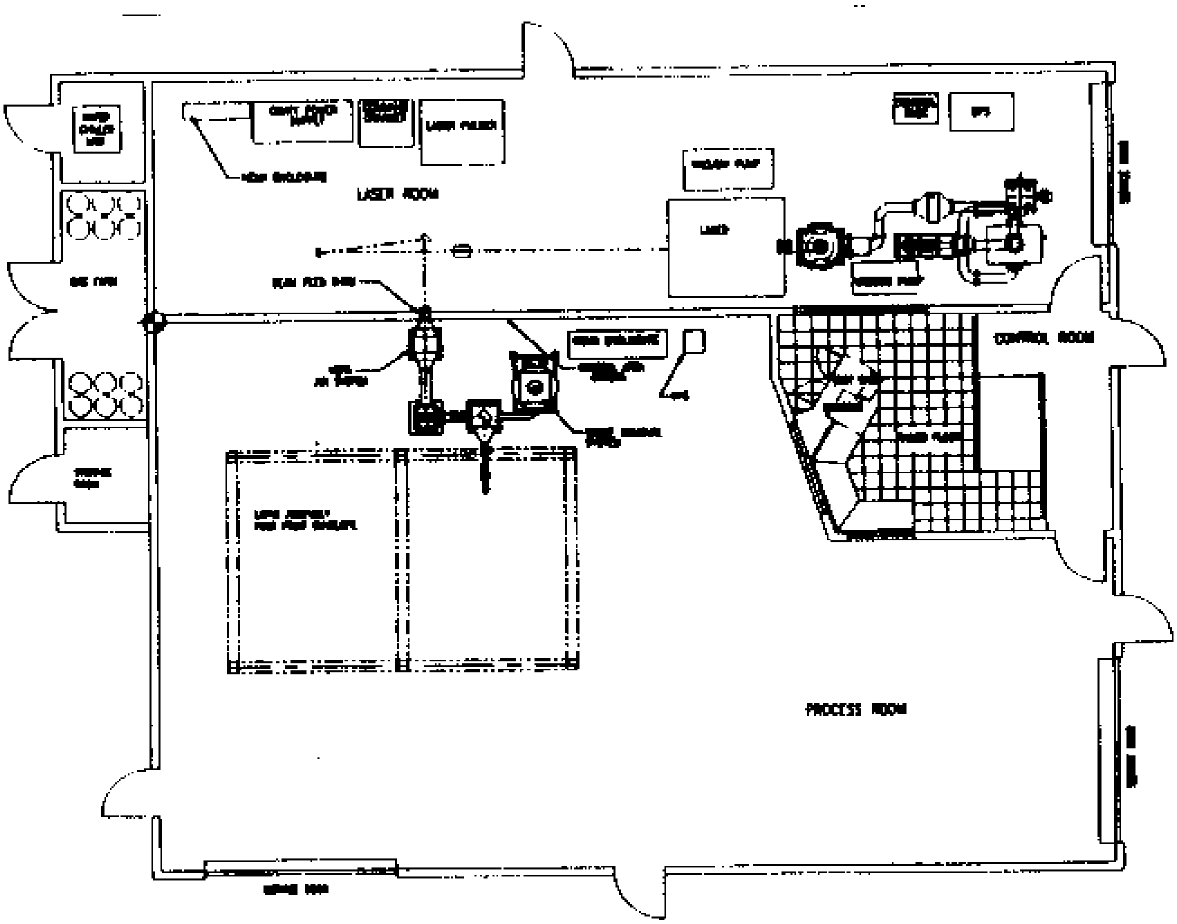

Figure 3. - LADS Systems Layout

3.2.2.1 Pulsed laser. The pulsed laser subsystem was fabricated by Plasmatronics Inc., a subsidiary of BDM Federal Inc., and subsequently integrated, tested, and installed in the LADS. The laser is a 5 KW average power, rapid pulsed CO2 laser, Plasmatronics' model 8800 12. The characteristics of the laser are:

- Max avg. power — 5400 watts - rectangular beam; 4200 watts - round beam
- Energy per pulse — 18 to 36 joules, variable rect. beam; 14 to 27 joules, variable round beam
- Repetition rate — O to 150 PPS, variable on demand

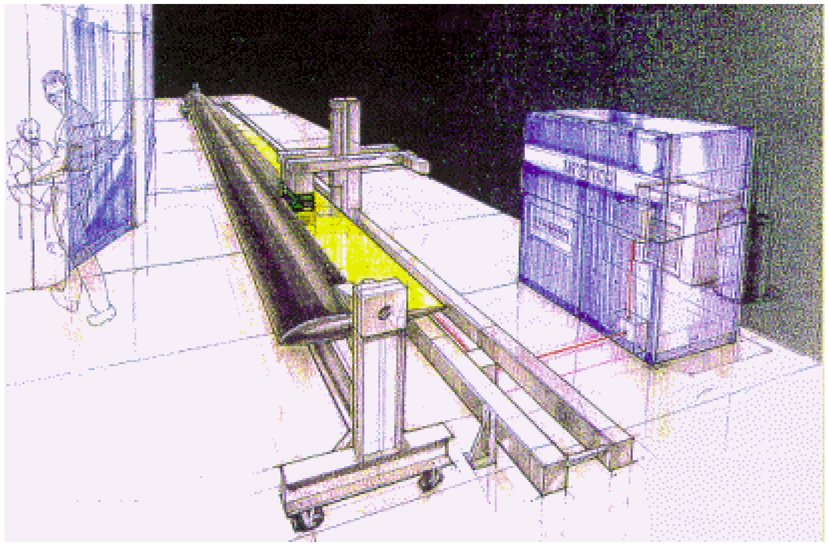

Figure 4. - Artist Drawing of ALPS for Helicopter Rotor Blades

SECTION IV - TEST PROCEDURES AND PRACTICES

4.1 NAVY ALPS PROGRAM.

4.1.1 Phase I of the ALPS program was divided into two tasks, phase Ia and Phase Ib. Phase Ia, completed in Feb 91, required Navy approval before InTA could proceed to phase Ib. The Navy determined that a phase Ia supplemental test was needed, which would repeat the temperature rise and tensile tests and further test the effects of exposing sulfuric acid anodize to laser light. The approval to begin the phase Ia supplemental tests and phase Ib was given in Jul 91.

4.1.2 In phase Ia, InTA prepared procedures to fully define the test methodologies and identified the test panels by using a numbering system. Any specimen cut from a panel was marked with the same number as the panel. Twelve inch square panels, provided by Grumman, were identified by a designation that is a combination of the test phase (1A), a one-hundred-series number for the type of substrate and coating (100, 200, etc.), and a letter code for the stripping plan (C for control, O for overexposed, and S for single strip cycle). The specific test plan was developed in a matrix, table 1, to indicate the actual number of tests performed on each sample. The following sections describe, in detail, the procedures used to perform the tests.

4.1.2.1 Aircraft substrates tested. The following aircraft metallic and composite substrates were laser stripped and analyzed:

- Aluminum 7075-T6C X .032" thick
- Aluminum 2024-T3C X .032" thick
- Aluminum 2024-T3B X .032" thick
- Fiberglass/Epoxy (GM3006), woven 4-ply (0/45)S
- Carbon/Epoxy (AS4/3501-6), 14-ply *(0101+45145101+45145)S*
- Carbon/BMI (HMF398/V378A), woven 4-ply (0/45)S
- Carbon/Epoxy (HMF 133/3501-6), woven 4-ply (0/45)S
- Carbon/Epoxy IM6/3501-6), 14-ply *(0101+45145101+45145)S*

4.1.2.2 Aircraft substrate pre-treatment and coatings tested. The coating scheme used for both metallics and composites (one strip cycle, over exposed) consisted of polysulfide sealer, epoxy primer, and a polyurethane topcoat. The pre-treatments for the aluminum substrate specimens were as follows:

- Chromic Acid Anodize on Aluminum 7075-T6C and Aluminum 2024-T3C
- Sulfuric Acid Anodize on Aluminum 2024-T3B

4.1.2.3 Controls. Unpainted specimens of each metallic and composite substrate listed above were analyzed using the following methodologies:

- (visual inspection all specimens

- Conductivity testing — one each, metallic
- Cross sectioning — two each, metallic/composites
- Tensile testing — two each, metallic
- Surface roughness — one each, metallic
- Surface analysis (SEM/EDAX/Auger) — one each, metallic/composites

4.1.2.4 Overexposed strip cycle. All specimens were coated with polysulfide sealer, epoxy primer, and polyurethane topcoat. Specimens of each metallic and composite substrate listed above-were stripped and then purposely overexposed to the strip laser so that any degradation* to the substrate could be analyzed. The test methodologies used in the analysis included:

- Visual inspection — all specimens
- Surface cleanliness — all specimens
- Conductivity testing — one each, metallic
- Cross sectioning — two each, metallic/composite
- Tensile testing — two each, metallic
- Surface roughness — one each, metallic
- Temperature rise — one each, metallic/composite
- Surface analysis (SEM/EDAX/Auger) — one each, metallic/composite
- Paint adhesion — one 2024-T3C aluminum, one AS4/3501-6 carbon/epoxy

4.1.2.5 One strip cycle. AU specimens were coated with polysulfide sealer, epoxy primer, and polyurethane topcoat. Specimens of each metallic and composite substrate listed above were stripped using the laser and then analyzed using the following test methodologies:

- Visual inspection — all specimens
- Surface cleanliness — all specimens
- Conductivity testing — one each, metallic
- Cross sectioning — four each, metallic/composites
- Surface roughness — one each, metallic
- Temperature rise — one each, metallic/composites
- Surface analysis — one each, metallic/composites
- (SEM/EDAX/Auger)
- Paint adhesion — one 2024-T3C aluminum
- one AS4/3501-6 carbon/epoxy

4.1.2.6 Parametric study. The laser and raster parameters were varied (i 30 % where possible), nominal laser parameters established, and stripping efficiency measured for:

- Laser peak power = 625 KW - 833 KW

- Laser pulse width = 6-8 ps
- Average laser power density = 5 J/cm2 on the stripping surface
- Laser energy density on the surface = 5.6 W/cm2

4.1.3 Phase Ia test results.

4.1.3.1 Testing in phase Ia showed minor changes in the surfaces of the anodized aluminum substrates after paint stripping. Evidence of the changes was seen in the surface roughness, electrical continuity, SEM and metallographic tests. However, subsequent testing demonstrated that the slight melting effects seen in the 100- and 200 series samples can be avoided by a small reduction in energy density of the laser beam. No simple method of eliminating crazing was found, but indications are that chemical conversion coatings routinely applied before repainting will compensate for this problem. Further study is recommended to determine how to eliminate the crazing.

4.1.3.2 Differences between the anodized layer on 200 series samples and the 300 series was attributed to thickness of the coating (0.0005 inch and 0.0002 inch) and having been applied by a sulfuric acid process rather than a chromic acid process. Lowering the energy density to the lower limit did not affect the melting and anodize removal observed on the 300 series samples. To determine the cause of this effect and how to avoid it requires further analysis. One possibility for trial in a follow-on is to use longer pulse widths and lower peak power.

4.1.3.3 Scratch tests on the surfaces indicate that the remaining anodize was tightly adhered and suggest that the stripped panels could be successfully repainted.

4.1.3.4 Mechanical tests showed a few small differences in properties between the control and laser stripped samples. Some of these differences were due to failures at score marks from the paint adhesion tests or at punch marks. Other differences did not appear to be statistically significant. SEM and metallographic examination revealed no evidence that the base metal of the samples had been compromised in any way. Additional testing is required to determine if there is any possibility that the laser stripping can alter the properties of the base metal.

4.1.3.5 On the composite samples, when they were intentionally overexposed, the laser did remove mater al from the substrate. However, the extent of damage, which was less severe than expected, was limited to partially removing the composite matrix material from the top surface of the substrate and from the top 0.0005 inch of the fiber bundles. There was no evidence of damage to the composite substrates for the single strip samples.

4.1.3.6 All of the metallic specimens (1A-100, 1A-200, 1A-300) passed the surface cleanliness test prior to painting. Satisfactory results were achieved in painting the panels, and all the panels that received the adhesion test passed.

4.1.3.7 For the paint stripping tests the 1A-100 0, 1A-200 S, and 1A-200 0 specimens were stripped with a diagonal dither pattern. The remaining samples were stripped using a quarter-step box dither pattern (1 dither = 16 raster patterns, 1 raster pattern = 784 pulses). Two dither patterns (32 raster patterns) were required to strip the aluminum samples (paint thickness approximately 9 mile). The stripping parameters for all samples were:

- Laser energy density = 5 J/cm2
- Laser average power density = 64 mw/cm2
- Laser pulse width (FWHM) = 6 - 8 microseconds
- Average laser peak power = 735 KW
- Laser repetition rate = 10 Hz

4.1.3.8 Visual inspection:

4.1.3.8.1 Pre-painting:

- 1A-100 - There were wet streaks across the panel from anodize and very light surface scratches (handling marks). There were heavy scratches under the anodize clamps.
- 1A-200 - There was some wet streaking from the anodize and a large scratch in the middle of the panel with the grain. There was an attempt to paint the panel to leave this on the back. There were heavy scratches under the anodize damps.
- 1A-300 - There were bum marks from anodize clamps on the edges and black streaks under the clamp marks.
- lA400 - There was light scratching on the comer from removing the peel ply layer and edge fractures from cutting (less than 1/8").
- 1A-500 - There was scratched dimpling on the painting surface and light wrinkling on the tool surface.
- IA-600 - There was a slight edge distortion., which was removed when the panel was trimmed. The painting surface had no defects.
- 1A-700 - The painting surface had no damage.
- 1A-800 - There was a slight depression on the painted surface and slight wrinkling on the tool surface.

4.1.3.8.2 Pre-stripping:

- The painted panels had a few bumps due to foreign particles and fibers trapped in the coating.

- 1A-100 S, lA-300S, 1A-500, lA-600-S, lA-700-S, and lA-800-S contained deep scratches in the paint and substrate that were produced as part of the paint adhesion tests.

- Aluminum control panels generally had a uniform semi-gloss appearance. The exceptions were a few randomly positioned streaks on samples 1A-100 C and 1A-200 C that were more glossy and/or matt in appearance. Such streaks are typically the result of non-uniform chemical cleaning prior to anodizing.

- There were no anomalies observed on the composite panels.

4.1.3.8.3 Post-stripping, aluminum samples:

- The single strip and over strip aluminum samples exhibited on a few small islands of polysulfide sealant remaining on the surface (less than 0.19t of the stripped area).

- Random matt and glossy streaks were apparent on most of *the* aluminum samples. These streaks appeared identical to the random streaks on the control samples, and it was concluded that these were due to chemical cleaning prior to anodizing rather than to laser stripping effects.

- Fairly regular patterns of matt and semi-gloss areas that matched the dither pattern.

- Samples stripped with a diagonal dither exhibited faint diagonal stripes (1A-100-0, lA-200S, and lA-200-O).

- Samples stripped with a quarter-step box dither exhibited plaid patterns (1A-100 S, 1A-300 S, and lA-300-O). The pattern was less apparent op the 300series samples, particularly on the overexposed sample.

- The frequency of the stripes and plaid patterns matched the dither pattern used; that is, one matt and one semi-gloss stripe per step for the diagonal dither and four matt and four semi-gloss stripes per step for the quarter-step box dither.

4.1.3.8.4 Post stripping, composite samples:

- Overexposed composite samples appeared darker in color than their respective control samples and had a plaid pattern that matched the dither pattern in the ablated area. The surface was smooth and tapered at the edge.

- There were minor amounts of the polysulfide coating still remaining near the " edges (within 1 inch) in fine lines.

- The single stripped samples exhibited the same plaid pattern to a lesser amount.

- Small islands of primer (less than 1% of the stripped area) remained

- The surface was tapered at the edges with darker lines across the surfaces of 1A-500 S, lA-S, and lA-70-S. The darker lines were small amounts of residue from ablation.

- Scratch lines on 1A-600 S and lA-700-S samples were due to the paint adhesion test.

4.1.3.9 Stereo microscopic inspection:

4.1.3.9.1 Inspection of the aluminum samples confirmed the anomalies observed during visual inspection. No additional anomalies were observed.

4.1.3.9:2 No anomalies were observed on the single strip composite samples other than a few small isolated spots where the substrate was exposed. The surfaces of overexposed samples fabricated from woven graphite fibers (lA-O, lA-O, and lA-70-0) exhibited approximately equal amounts of matrix material and exposed fibers. The surface of the- samples fabricated from non-woven fibers (tape) consisted of almost one hundred percent exposed fibers.

4.1.3.10 Surface roughness tests:

4.1.3.10.1 Pre-painting mean surface roughness measurements were made on the aluminum samples only. Table 2 shows the results of mean surface roughness values (Ra) measured before painting and cutting of samples. The roughness was measured vertically (against grain) and horizontally (with grain). In the vertical direction the samples were rougher. With one exception the roughness measurements were approximately 10 microinches. The exception was the 1A-100 sample measured across the grain. This had a roughness of approximately 20 microinches. The surface roughness measurements were performed in Grumman's Quality Engineering Laboratories using a model PKV/C3A Perthen profilometer.

4.1.3.10.2 Post-stripping mean surface roughness values (Ra) for each sample, both control and after stripping, were measured and recorded in table 3. Surface roughness measurements of control samples by Grumman and Surface Engineering allow comparison of instruments. Surface Engineering Laboratories used a Taylor-Hobson Surtronic Model 3. Immediately before use, Surface Engineering calibrated the instrument with Cali-Blocks, Inc., Mark II Precision Reference Specimen, which is traceable to the National Bureau of Standards.

- The 1A-100 control sample was invalidated since it was painted by mistake.

- The 1A-200 samples were very close, 11.2 vs. 12.4 microinches.

- The 1A-300 sample showed a significant difference between the two measurements. The roughest Grumman measurement, across the grain, was 10.8 microinches with a standard deviation of 2.6, whereas the Surface Engineering measurement was 32 i 13.7 microinches. The large discrepancy is enough to suggest that the test methodology needs improving. Two changes can be made to improve the tests: map the measurement location to insure measurements are made in similar regions each time, and increase the number of measurements on each sample.

- The 1A-200 overexposed sample set contained one point that can be discarded based on the other four points. The four points provide a 13.5 $\pm$ 1.29 microinch average deviation. The discarded point, at 22 microinches, is 6.6 standard deviation away from the average, justifying the elimination from the set. With this correction, the 1A-200 data does not support any increase in surface roughness after one strip cycle or after an over-strip cycle.

- None of the surface roughness measurements came close to exceeding the 125-microinch limit considered acceptable for critical areas. This 125-microinch limit for critical areas meets the F-14 specification, A51-CSS-026. Thus, the laser paint stripper does not generate unacceptable surface roughness. Therefore, with minor improvements, the testing methodology for the la test on surface is closed out.

4.1.3.11Conductivity testing revealed that the average resistance values were greater than 20 megohms for the control samples and 2 to 15 K ohms for the stripped samples (table 4). The overexposed samples produced resistance values that were slightly less than the single strip samples.

- Resistance values measured by touching the probe to the surface without dragging it produced resistance values that were almost always either greater than 20 megohms or less than 100 ohms. Very few intermediate values were measured out of several hundred tests. This indicates that the resistance values measured while dragging the probe are an average of a series of resistance values that are either greater than 20 megohms or less than 100 ohms.

- It is assumed that this condition is a direct result of the features seen in the anodized layer under SEM examination. Eliminating the changes to the anodized layer will eliminate the reduced conductivity testing.

4.1.3.12 SEM surface analysis:

4.1.3.12.1 The 100 series control sample (1A-100 C) exhibited a dimpled surface typical of chemically cleaned aluminum and the single strip sample (lA-10~S) exhibited crazing and micro-cratering.

- The crazing appeared to be a network of cracks in the anodize that was present to some degree across almost the entire stripped surface.

- The severity of micro cratering varied greatly from point to point on the sample. Areas that had a semi-gloss surface texture exhibited very few isolated craters, and areas that had a matt surface texture exhibited overlapping microcraters. The crazing was much less evident in these areas than in the areas without micro-cratering and in between the areas there was a gradual transition in the severity of the micro-cratering.

. • Examination of an area where the paint had been chemically (MEK) removed from the edge of the laser stripped area revealed that even the thinnest layer of paint prevented any crazing or micro-cratering.

4.1.3.12.2 The 100 series overexposed sample (1A-100-O) exhibited the same anomalies as the single stripped sample. However, the percentage of surface exhibiting micro-cratering was a little greater for the overexposed sample.

4.1.3.12.3 The 200 series samples exhibited surface features nearly identical to the 100 series control sample. Once again, the only difference observed was that the micro-cratering was somewhat more prevalent on the overexposed sample than on the single strip sample.

4.1.3.12.4 The 300 series samples exhibited surface morphologies significantly different from the 100 and 200 series samples. The control sample exhibited a dimpled appearance that was the result of selective removal of secondary phases in the substrate during chemical cleaning prior to anodizing.

- The entire surface of the single stripped sample (IA-300-S) exhibited a large number of small, roughly spherical features surrounded by even smaller irregular bumps. There was no evidence of any features matching those present on the control sample. At the edge of the stripped area, there was a narrow band of flake-like surface morphology between the paint and the bump-like features. Removal of the paint at the edge of the stripped area, by scrubbing with a swab soaked in MEK, revealed that the entire surface that had not been exposed by laser stripping was identical to the control sample. This cleaning process had a negligible effect on the surface morphology in the laser stripped area.

- The overexposed sample (lA-300-O) appeared identical to the single stripped sample (lA-300-S).

4.1.3.12.5 The micro-cratering in the 100- and 20~series samples and the irregular bumps on the 300-series samples appeared to be the result of melting and resolidification of something on the sample surfaces. Energy dispersive analysis indicated these features were anodize rather than a foreign matter. To better understand the mechanism for creating these features, a series of experiments was performed where the laser energy density was reduced (at the expense of stripping efficiency).

- It was found that by reducing the average energy density to 4.7 J/cm^2, the micro-cratering was eliminated in the 100 and 200 series samples. However, the crazing could not be eliminated until the energy density was reduced to 3.4 J/cm^2. NOTE: Within the parametric range of the application lab laser this energy density is below the threshold required for removal of the polyurethane top coat.

- At an energy density of 4.7 J/cm2 the spherical features and irregular bumps were still observed on the 300-series sample. Exposing the bare anodize to the laser pulse produced similar surface features. Damage to the anodize could not be eliminated until the energy density was reduced to below 3.4 J/cm2 (Energy density is below that required to remove the polyurethane top coat).

- The pulse width for the laser is less than desired. This is due to trade-offs the laser manufacturer made in optimizing the laser-for-laser paint stripping use. Extending the pulse width will lower the peak power while still delivering the energy necessary for coating removal. The laser has a full-width-at-half-maximum (FWHM) pulse width of 6 1ls, whereas the desired pulse width is between 20 -30 1ls.

4.1.3.13 Metallographic cross sectioning:

4.1.3.13.1 The anodize on the 100 series control sample (1A-100 C) appeared as a smooth, continuous, 0.0002-inch-thick layer on the aluminum surface. There were no anomalies observed in the anodize, cladding, or base metal.

4.1.3.13.2 The anodize layer on the single strip sample (1A-100-S) had a rougher surface than the control sample and contained narrow cracks. The degree of surface roughness varied from location to location on the cross section. The areas that appeared to have more of a matt surface texture looked rougher when examined on the metallographic cross section. The locations of the rougher surface features were consistent with the SEM analysis as well.

4.1.3.13.3 The cracking and surface roughness observed on the overexposed sample (1A-100-O) appeared identical to or only slightly worse than the single stripped sample.

4.1.3.13.4 Metallographic cross sections of the 200-series samples (lA-200-C, lA-200-S, and 1A-200-O) appeared identical to the 100-series samples.

4.1.3.13.5 It should be noted that this engineering data will be used to establish the size of the frame, since the larger the frame, the longer between pulses and more time the substrate has to cool.

4.1.3.14 Tensile testing:

4.1.3.14.1 The results of static tensile tests for the control and overexposed specimens are summarized in tables 6 and 7 for the 1A-100, 1A-200, and 1A-300 specimens. The tables list the values obtained for the ultimate tensile strength, F_{tu}, the 0.2 % yield strength, F_{ty}, the true fracture stress, S_f, the modulus of elasticity, E, the ultimate elongation, e_u, and the percent reduction in area % RA. Also, the average values for each material and condition are given, as well as the "B"-basis design values for F_{tu} and F_{ty} obtained from the Mill Handbook 5-E.

4.1.3.14.2 Tests on the lA-300-O specimens resulted in values of F_{tu} and F_{ty} higher than the "B"-basis values and within expected scatter as compared to the controls. However, the fracture stress and reduction in areas are 8 % - 10 % lower than the control specimens, and the average elongation is only 11.2 % as compared to the minimum elongation of 15 %. The values of F_{tu}, F_{ty}, and S_f for the lA-200-O specimens were virtually identical to the values obtained for the control specimens. Only the elongation values obtained for the overexposed specimens were slightly below the minimum Mill Handbook 5-E elongation for this material.

4.1.3.14.3 As shown in table 7, the ultimate and yield strengths of the overexposed 1A-100 specimens were virtually identical to the values obtained with the control samples and were appreciably higher than the "B"-basis values. The fracture stress for the overexposed specimens was slightly (4%) lower than for the control samples but the reduction in area was 18 % lower. Also, the values for elongation for both the control and overexposed specimens were below the minimum value of elongation (15%).

4.1.3.14.4 Tensile tests were inadvertently performed on single strip cycle specimens. This was not required in the test plan, and the results are not included as part of this report. Several of the specimens broke on the score marks from the paint adhesion test rather than in the center. Although not significant in this round of testing, any future tests would be carefully monitored to avoid scoring in the tensile test areas.

4.1.3.15 Parametric study:

4.1.3.15.1 A Lumonomics model 20D detector was used to measure pulse energy from the laser. This detector was a piezoelectric crystal-based unit that generates a peak voltage output proportional to the total energy impressed onto it. A detector face with a diameter of 2 inches accommodated the entire raw 'beam. The output was connected to an HP54503A 500 MHz digitizing oscilloscope in order to measure peak voltage. Energy measurements were made using the 20D detector connected to the oscilloscope via 50-ohm coaxial cable.

4.1.3.15.2 A Hamamatsu model B749 photon-drag detector was used to measure laser pulse width.' This detector is a germanium-based device that generates a voltage proportional to the power applied to it. It has one nanosecond rise time and can accurately track the instantaneous power intensity characteristic of the laser beam. The detector was connected to the HP54503A oscilloscope via 50-ohm coaxial cable. This allowed examination of the overall pulse shape's initial spike and transition to an elongated tail. Details could be shown for pulse width measurement of the initial spike by the full-width-at-half-maximum (FWHM) method. These values are on the order of 250 ns. Also, this method provides the means of measuring the tail, typically 6-8 microseconds. The energy within this time domain is predominantly responsible for the stripping process.

4.1.3.15.3 Several laser beam parameters were varied in order to observe the effects on stripping efficiency. These observations were done as a verification of the initially-chosen stripping parameters.

4.1.3.15.4 Laser energy density is by far the most crucial factor and was originally established at 5 J/cm2. The pulse repetition rate was held constant throughout the stripping process at 10 Hz. This gave an average power density of 50 W/cm2.

4.1.3.15.5 The energy density (and hence power density) was decreased until stripping was no longer achievable. This state occurred when the energy density was 4.0 J/cm2 and power density was 40/W cm2. At this point, paint was merely bleached, even after many repetitive pulses which overheated the sample. Therefore, a laser energy density of 5 J/cm2 was used during sample stripping.

4.1.3.15.6 The laser pulse width, FWHM, was increased from approximately 5.3 to 6.8 microseconds by varying the gas mixture and the laser output coupler. The result of this was an increase in beam energy and a 15 % increase in stripping efficiency.

4.1.3.15.7 A Spiricon model LMP 32X32-161 pyro-electric detector matrix array, controller and frame grabber, and PC-AT 386 personal computer, were used to capture the output beam profile. This method allowed viewing and determination that the energy distribution across the beam is fairly uniform, which is very desirable as it yields even material removal and aids stripping efficiency by placing fewer restrictions on raster control.

4.1.4 Phase Ia conclusions.

4.1.4.1 The laser stripping process does not appear to have an effect on metallic base material or cladding. All testing to date is in agreement with this finding. This was true for both single strip cycle samples and overexposed.

4.1.4.2 Using the nominal parameters established for the laser pulse width in the phase Ia tests, the laser damages the anodizing on clad or bare substrates. The damage takes the form of cracks and craters. It is assumed that the cracks, and not the craters, are the cause of the reduced resistance observed in the metallic samples.

4.1.4.3 The anodizing was well adhered to the substrate everywhere it was examined. Repaintability is expected to be excellent in all samples, based on SEM and micrographic examination.

4.1.4.4 The anodize layer on the 300-series control sample (lA-300-C) appeared as a smooth, continuous, 0.0005-inch-thick layer on the aluminum surface. No anomalies were observed in the anodize layer or the base metal.

4.1.4.5 The anodize layer on the single stripped sample lA-300-S) was very thin (0.0001 inch) and the anodize surface was very irregular. Numerous spherical particles (roughly 0.0005-inch in diameter) that appeared to be anodize were also present on the surface. At the edge of the stripped area, the thin layer of anodize left on the surface was covered by what appeared to be flakes of anodize. The overexposed sample (lA-300-O) appeared identical to the single stripped sample.

4.1.4.6 The composite single strip samples (lA4WS through lA-800-S) exhibited a continuous layer of polysulfide sealant from 0.005 to 0.011 inch thick (table 5). Examination of the over strip samples (lA-O through lA-800-O) revealed that most of the matrix material had been removed from the top surface of each sample. However, it appeared that the matrix material within the exposed fiber bundles was unaffected by the laser except for the top two or three fiber diameters in the first ply.

4.1.4.7 Measurements of sample thickness, by use of a filar eye piece on the microscope, revealed that the amount of material removed from the overexposed samples was less than the variation in thickness of the overexposed and control samples (table 5).

4.1.4.8 Temperature rise testing revealed that the thermocouples were placed too far from the painted surface to produce acceptable data. The use of this data requires a model of the heat flow to extrapolate between the measurement point and the surface. The surface temperature therefore becomes more a function of the model than of the measurements. Noise in the data acquisition system plus low measurement readings severely limits the accuracy of the measurements which translate through the model to become a very large error in the extrapolated sub-surface temperature.

4.1.4.8.1 A new plan for making temperature measurements much closer to the painted surface is required. Since these measurements will be closer to the area of interest, the extrapolated data will be less model dependent. In addition, the time response will be greatly improved over the measurements of data, since a much smaller thermal mass lies between the heat source and the measurement.

4.1.4.8.2 The thermocouple in this set of measurements was useful in establishing the bulk temperature rise in metallic and composite substrates. The maximum temperature rise in the metallic was 9.2 ° C, and the maximum rise in composites was 17.0 ° C.

4.1.4.9 No damage of any type was observed in the single strip cycle composite samples. The overexposed samples showed a removal of matrix material to a depth of 2-3 fiber diameters in the first ply. This region never exceeded 0.002".

4.1.4.10 Surface roughness may have been increased in the metallic samples due to laser stripping, but the data is not self-consistent. Nonetheless, none of the surface roughness measurements even approached one half of the required critical area specification.

4.1.4. 11 Some of the mechanical testing on the metallic samples was not properly carried out. The score marks from the paint adhesion tests compromised one set of data, and failure of control samples to meet specifications compromised the other questionable data. It is recommended that these tests be repeated with twice the original numbers of samples to insure confidence in the results.

4.1.5 Phase Ia recommendations.

4.1.5.1 Further studies should be conducted to determine the cause(s) of the anodize melting and crazing and to identify methods of avoiding these phenomenon. These studies should include laser pulse width increases and improvements in beam uniformity.

4.1.5.2 The temperature measurement methodology should be modified to improve experimental temperature rise data and the peak temperature rises should be re-measured.

4.1.5.3 The mechanical property tests should be repeated to establish whether or not laser paint stripping alters the mechanical properties of the substrates. Care should be taken to assure that paint adhesion tests are done in a way that does not leave score marks across the tensile test specimens.

4.1.5.4 The surface roughness measurements should be repeated on 100- and 300-series samples to validate the previous data.

4.1.6 Phase Ia supplemental, test plan. The procedures and methodologies for the phase Ia supplemental tests were fully defined and put in matrix form in table 8. The matrix indicates the actual number of tests performed for each sample. Twelve-inch-square panels were fabricated by InTA with the preparation and coatings applied to military specifications. All panels were inspected prior to and after painting. The panels were identified by a designation that is a combination of the test phase, a 100-series number for the type of substrate and coating (101, 201, etc.) and a letter code for the stripping plan (C for control, O for overexposed, and S for single strip cycle). Any specimen cut from a panel was marked with the same number as the panel. The following sections describe, in detail, the procedures used to perform these tests.

4.1.6.1 The following aircraft metallic and composite substrates were stripped and analyzed:

- Aluminum, 7075-T6C
- Aluminum, 2024-T3C
- Aluminum, 2024-T3B
- Carbon/Epoxy (AS4/3501-6)
- Carbon/Epoxy(HMFl33/3501-6)

4.1.6.2 The coating scheme used for both the metallic and composites (one strip cycle and overexposed) consisted of epoxy primer and a polyurethane topcoat. Pre-treatments for the aluminum substrate specimens were as follows:

- Chromic acid anodize –
  -- Aluminum, 7075-T6C (lA-101-C, lA-101-O, lA-101-S)
  -- Aluminum, 2024-T3C (lA-201-C, lA-201-O, lA-201-S)

- Sulfuric acid anodize - Aluminum 2024-T3B (lA-301-C, lA-301-O, lA-301-S)

4.1.6.3 For control, unpainted specimens of each metallic and composite substrate were analyzed using the following test methodologies:

• Visual inspection	all specimens
• Conductivity testing	(1) each, metallic
- • Cross sectioning	(2) each, metallic/composites

- Tensile testing (2) each, metallic
- Surface roughness (1) each, metallic
- Surface analysis (SEM/EDAX/Auger) (1) each, metallic/composites

4.1.6.4 For the overexposed strip cycle tests all specimens were coated with epoxy primer and polyurethane topcoat. Specimens of each metallic and composite substrate were stripped of paint and then purposely overexposed to the strip laser so that any degradation to the substrate could be analyzed. The test methodologies used in the analyses included:

• Visual inspection	all specimens
• Surface cleanliness	all metallic
• Conductivity	(1) each, metallic
• Cross sectioning	(2) each, metallic/composites
• Tensile testing	(2) each, metallic
• Surface roughness	(1) each, metallic
• Temperature rise	(1) each, metallic/composites
• Surface analysis (SEM/EDAX/Auger)	(1) each, metallic/composites
• · Paint adhesion	(1) each, aluminum 2024-T3C and carbon/epoxy (AS4/3501-6)

4.1.6.5 For the one strip cycle tests all specimens were coated with epoxy primer and polyurethane topcoat. Specimens of each metallic and composite substrate were stripped using the laser and then analyzed using the following test methodologies:

• Visual inspection	all specimens
• Surface cleanliness	all specimens
• Conductivity testing	(1) each, metallic
• Cross sectioning	(4) each, metallic/composites
• Surface roughness	(1) each metallic
• Temperature rise	(1) each, metallic/composites
• · Surface Analysis (SEM/EDAX/Auger)	(1) each, metallic/composites
• Paint adhesion	(1) each aluminum 2024-T3C and carbon/epoxy (AS4/3501-6)

4.1.7 Phase Ia supplemental, test results. The phase Ia supplemental test program examined in more detail the effects observed in phase Ia. Phase Ia flagged three specific areas for additional testing: temperature rise, anodize crazing/cratering, and tensile testing. The following subsections will review phase Ia findings and discuss both phase Ia and phase Ia supplemental test results and why these results proved to resolve the concerns established in phase Ia.

4. 1.7.1 Post-strip analysis of anodize coating. In phase Ia there were minor changes in the anodize on the surface of aluminum substrates. Evidence of these changes was seen in the surface roughness, electrical continuity, SEM, and metallographic tests. The anomalies appeared as crazing and micro-cratering. The specimens coated with sulfuric acid anodize showed a greater severity in these anomalies between single stripped specimens, and over-stripped specimens did not change. This suggested that the anodize is affected in the first few passes of the laser, once the anodize is exposed to direct laser light. In the post-phase Ia analysis, and as a precursor to repeating the tests in phase Ia supplemental, there were hot spots present in the laser beam after the final optics. This meant that the beam was not homogenized and was heating some areas within the laser footprint more than others. This would explain the cracking and melting.

4.1.7.1.1 The solution was to use a prism in the optics setup to homogenize the laser beam. The prism would divide the beam into four quadrants and then converge the four beamlets back into one homogenized beam. This reduced the hot spots dramatically.

4.1.7.1.2 Also, there was not enough control over the servos that moved the mirrors for rastering and dithering. When the encoders were on the edge of a count they would sometimes move an additional count which made the rastering inconsistent. The encoder resolution was 2500 counts. The system was modified to increased the resolution to 10,000 counts. This enhanced the consistency of the rastering and eliminated overexposure of the substrate to laser pulses in areas that did not require additional pulses.

4.1.7.1.3 With these modifications the test results showed that the stripping cycle became consistent.

·

- Visual examination of panels prior to stripping revealed no significant anomalies and after stripping the panels exhibited a uniform metallic gray color (in contrast to the previous Ia samples that had exhibited a mottled appearance).

- SEM revealed that the control panels exhibited a network of fine cracks or crazing. This effect is common in anodizing and is not considered a defect. Exposure of the anodize to the laser during stripping appeared to eliminate the crazing. In addition, the anodize appeared somewhat rougher after stripping, which is a positive impact in that paint will adhere better to the substrate.

- For comparison, samples were stripped using the lasers of two other companies. Both of these samples appeared very similar to the ones stripped by InTA.

4.1.7.1.4 Metallographic cross sections of the control and stripped samples revealed that anodize thickness on both the chromic acid anodize (lA-101-C and lA-201-C) and sulfuric acid anodize (lA-301-C) samples was 250 microinches thick. After stripping, the anodize surface was rougher but still intact across the surface of the aluminum. There was no evidence that stripping altered the cladding or base metal in any way.

4.1.7.1.5 Conductivity testing was performed using the standard set-up with a battery, light bulb, and probe in a configuration that makes the light bulb light up any time the probe makes electrical contact with the substrate. This test was performed by dragging the probe in a Z-pattern over all the single strip and over-strip samples. In no case did the bulb light up, which indicates that the anodize was intact even after overstripping the samples.

4.1.7.1.6 Average roughness testing was performed both before and after stripping and overstripping. The highest roughness value measured was 69 microinches (table 9) which is well within the 125-microinch limit of the F-14 specification, A51-CSS-026.

4.1.7.2 Tensile testing. In phase Ia the aluminum, 2024-T3B (1A-300-O) overstripped sample showed a reduction in fracture stress and % RA of 8-10 when compared to the control! specimen. Also, the average elongation was only 11.2 % as compared to 15.5 % for the control specimen. There is no requirement in MIL-HDBK-SE for elongation in the longitudinal direction for this material. All areas ($F_{'u}$, F_u, S_f, etc.) passed the testing criteria. The only explanation for the low elongation values would be overheating the substrate during the laser process. Based on the phase Ia temperature rise tests, this did not happen. Therefore, the results were inconclusive, which was the reason for additional testing in phase Ia supplemental.

4.1.7.2.1 The tensile specimens were tested per ASTM E4. The values for ultimate tensile strength, yield strength, true fracture stress, reduction in area, modulus of elasticity, and elongation were determined for five specimens for each sample type (tables 9, 10, and 11). If one of the five fractured in a questionable manner, such as through a gauge mark, the results were discarded and an additional specimen was tested.

4.1.7.2.2 Nearly all results met the requirements of MIL-HDBK-5D. The only exception was the yield strength for the 2024-T3 bare overstripped samples. This value, 46,920 psi, was slightly lower than the control sample, 48,520 psi, and the MlL-HDBK-5D-basis requirement, 48j000 psi (table 12). Since previous test results indicated that the yield strength for the overstripped sample was slightly higher than for the control (57,800 psi, table 13) this slightly low value was of little concern. The differences in property values between control and overstripped samples amounted to only a few percent, even in the worst case.

4.1.7.3 Temperature rise testing. In phase Ia, the temperature testing revealed that the thermocouples were placed too far from the painted surface to produce acceptable data. The use of this data required a model of the heat flow to extrapolate between the measurement point and the surface. The surface temperature, therefore, became more a function of the model than of the measurement. In phase Ia supplemental, the thermocouples (T.C.) were placed at the substrate surface (and then the coatings were applied) with four additional thermocouples placed, one, two, three, and four mils below the surface, respectfully. The results follow:

4.1.7.3.1 Thermal data were taken with low-mass, type- 'T', T.C., Model CO2-T OMEGA Engineering. The copper-constantan junction tips are 0.0005-inch-thick. The T.C. output was amplified 247.3X and cold-junction compensated to 0°C (32°F) with an Analog Devices AD565 T.C. amplifier. This amplifier, although designed for type "K" T.C., compensates the type '~' T.C.

within 11 microvolts, which is correctable. The output voltage was converted to temperature according to NIST-traceable tables for °C reference T.C.s. The T.C. amplifier output was recorded with an H-P 54503A digitizing oscilloscope.

4.1.7.3.2 Proximity to the Lumonomics discharge-pump laser caused considerable noise, which was reduced during the experimental program by refining the noise filtering technique. After the noise filtering was optimized, the peak amplitude recorded corresponded to about 85°F temperature rise, but the duration is less than one-third of the laser pulse duration of 20 microseconds. Some noise spikes were higher, and many times none were seen.

4.1.7.3.3 The rise time of the thermocouple and amplifier was about 20 microseconds, comparable to the laser pulse duration. For thermocouples attached to or mounted in substrates, the rise times were tens of hundreds of milliseconds. Consequently, the noise spikes were clearly unimportant except to mark the beginning of the laser pulse. The slow fall time was even more evident, providing assurance that the peak value of the pulse was not significantly degraded by the rise time.

4.1.7.3.4 Thermocouples were mounted on the composite and aluminum samples with conductive silicone paste because it matched the thermal conductivity of aluminum very well and even the best thermally conductive epoxies had conductivities that were only a fraction of the aluminum. The thermocouples were mounted on one end of the 1- X 6-inch pieces of the various substrates.

4.1.7.3.5 For the temperature rise measurement, a worst case energy density at 6.1 J/cm2 was used and the rise was measured in two ways. First the laser was pulsed on top of the thermocouple at a very slow rate (once every 20 seconds). This was intended to show the instantaneous temperature rise for a single pulse. The second was to raster the beam over the sample. The size of the raster pattern was varied to duplicate stripping at higher rates such as 1000 Hz. This was intended to show the bulk temperature rise of the substrate. During the experiments, the samples were thermally insulated from the mounting plate by several layers of paper

4.1.7.3.6 Instantaneous temperature rise for aluminum was in the order of 25° to 35° F. This temperature rise is negligible considering that most aluminum must be aged at temperatures above 400 °F for several minutes to change the properties.

4.1.7.3.7 Most of the aluminum samples were used for bulk temperature rise testing using a 5 X 5 raster pattern that covered the last 1 1\4 inches of the sample. This is equivalent to stripping a full 28 X 28 raster pattern at 314 Hz. For single strip, the temperature rise ranged from 150° to 205° F after approximately 14 raster patterns (table 13). An additional six pulses resulted in typically no more than another 10-degree temperature rise. Consequently, even overstripping does not appear to cause serious temperature rise for aluminum substrates.

4.1.7.3.8 The instantaneous temperature rise values showed no consistent trend in the region between one and four thousandths of an inch below the surface. Consequently, it is not practical to determine the surface temperature of the aluminum from the data collected other than to say there is no evidence that it is significantly higher than the bulk temperature. Attempting to extrapolate this type of data directly into the anodize is not practical since the thermal conductivity of aluminum oxide is less than one tenth that of the aluminum alloy.

4.1.7.3.9 The composite samples were approached in a manner similar to the aluminum. However, the instantaneous temperature rise was on the order of 70° to 140° F. Because this value was so high, it is much more important for the composite stripping than for the aluminum stripping. The majority of composite samples were used to determine the instantaneous temperature rise.

4.1.7.3.10 The effects of thermocouple depth and paint removal were observed. Because of variations, not all of the data is useful. Variations included:

- 2 epoxies
- thermocouple mounting variations
- over-layer thickness and position
- painting variations
- errors in laser - to - TC alignment
- two composite lay-up techniques

4.1.7.3.11 Despite these problems, a family of consistent data was obtained. In all cases, the highest values were the most satisfactory, since most errors would have given reduced readings. As expected, the peak temperature and rate of rise increased as paint was removed from the surface. Data shows that the instantaneous temperature rise is limited to about 160°F at 0.001 inches deep and 100°F at 0.003 inches deep as long as some paint remains on the surface of the composite. Additional exposure of the substrate after the paint is removed causes rapid increase in the single-pulse temperature rise.

4.1.7.3.12 Additional composite samples were stripped by rastering over patterns of 3 X 3 and 5 X 5 at 10 Hz to duplicate the rates of heat input that would be encountered while stripping a full 28 X 28 raster pattern at higher pulse rates. The rates simulated were 871, 314, and 87 Hz. The raster pattern was aligned so that the center pulse was lined up above the thermocouple, which was 0.002 inch below the surface. The temperature rose more quickly once the paint was removed, which reinforces the decision to strip the composites only down to the primer.

4.1.7.3.13 The bulk temperature rise data for the three stripping rates covers the processing range from 10 pulses, which starts to expose primer, to 14 pulses, which starts to expose substrate. The temperature rise produced by the highest rate (871 Hz) may make it necessary to strip a larger pattern than 28 X 28 to reduce the temperature rise for composites.

4.1.8 Phase Ia supplemental conclusions.

4.1.8.1 The phase Ia supplemental task proved to be a worthwhile effort in that it answered the questions that arose in the phase Ia testing.

4.1.8.2 The anodize cracking can virtually be eliminated, leaving a surface that maintains its integrity in preventing corrosion and, at the same time, providing a surface that promotes better paint adherence.

4.1.8.3 The temperature rise testing proved that the substrates, regardless of make-up (metal or composite), remain well within the temperature ranges for sustaining the material properties exhibited in the pre-strip state.

4.1.8.4 The tensile testing showed that the material properties are unaffected by the heat generated by the laser. Although the yield strength of the aluminum, 2024-T3B was slightly lower than the control sample, the values show no cause for concern. This is because the yield strength value exhibited in phase Ia for the same material actually proved slightly higher than the control sample.

4.1.8.5 Primary testing of the laser paint stripping method is positive proof that this method is a viable one. Phase lb will further substantiate this by analyzing a greater number of substrates in rigorous, four strip cycle testing. SEM analysis of the sample stripped by a laser other than InTA's test laser shows the same positive results, which suggests that the specified parameters are correct.

4.1.9 Phase Ia supplemental recommendations.

4.1.9.1 Continue with phase lb tests.

4.1.9.2 Initiate phase I1.

4.1.10 Phase lb test plan. In phase lb the tests were performed on composites and - addressed the Navy's concerns about possible overheating of composite substrates. The Navy identified the maximum safe exposure temperature at 121 ° C (250 ° F). It should be noted that this number is conservative even for long-term exposure (the time at maximum temperature during laser paint stripping is on the order of milliseconds).

4.1.10.1 The objective of phase lb testing was to determine the maximum rate at which the composite samples may be stripped without compromising the properties of the material by overheating. The front-to-rear temperature change was to be determined in order to effect a bulk temperature rise of no more than 121 ° C (250 ° F). Tests were also implemented to allow cross-section analysis of samples in which bare composite had been exposed to numerous laser pulses.

4.1.10.2 Four steps were executed to achieve the goals of temperature rise testing. The panels used for this effort consisted of graphite epoxy and fiberglass. The graphite epoxy was coated with primer and either polyurethane top-coat, rain erosion coating, or walkway coating. The fiberglass was coated with primer and polyurethane top-coat. The graphite epoxy consisted of AS4 woven fabric (4 ply [0/45] S), and 3501-6 resin, which has a 163 ° C (325 ° F) service temperature. The GM 4001-G42 fiberglass has a service temperature of 204 ° C.

4.1.10.2.1 The first step used graphite/epoxy paddles to determine the single pulse repetition frequency (PRF) at which to strip the graphite samples. PRF is the frequency at which the laser pulse strikes a particular point. When the laser is being rastered over the surface, the PRF is the rate at which the raster pattern is repeated. Thermocouples were mounted on the rear surface and at various distances from the front surfaces. Stripping paint from these paddles made it possible to determine front-to-rear temperature difference and to set up initial pulse repetition rates needed to meet the temperature requirements.

4.1.10.2.2 The second step consisted of applying this information to the full-size panels.

4.1.10.2.3 The third step was similar to the second, except that the PRI; was altered to produce five sets of data at various temperature exposures. This step was performed only on fiberglass/epoxy panels since the graphite results showed no cause for concern.

4.1.10.2.4 Step four was to metallographically cross section samples of all the substrates and coatings of step two.

4.1.11 Phase lb test implementation.

4.1.11.1 Paddle testing.

4.1.11.1.1 Paddle sample testing focused on graphite epoxy, since the majority of the composite panels to be stripped were graphite (table 14). The paddles were made of a heat dam, leaving a 0.75-inch square paddle, supported on a stalk approximately 0.15 inch wide and 0.12 inch long. This reduced conduction losses to the base of the sample.

4.1.11.1.2 Twenty-four paddles of three thicknesses were constructed (table 15). The thermocouples mounted near the front surface were fabricated by bonding them to the front surface and then placing a thin sliver of composite over them. The composite panels had a weave-like surface texture that was approximately 0.002 inch deep. Since this was also the depth at which the thermocouple was placed, both the paddle and the sliver on top of the thermocouple had their surface texture sanded off. The sliver was fabricated by bonding a small piece of composite to a block and then grinding it down until only a thin sliver remained. After the sliver was removed from the block, it was measured at a variety of locations to determine which area had the proper thickness. This location on the sliver was then mounted over the thermocouple junction with a very thin layer of epoxy adhesive. The front surface thermocouples were mounted in a similar fashion, except no sliver of epoxy was placed over the junction. The assembled paddles were painted with epoxy primer and polyurethane top-coat.

4.1.11.1.3 To simulate the final ALPS system, air was blown across the surface being stripped in the test set up. The cooling conditions were an air stream of 21 °C (70 °F) and 200 feet-per-second velocity, impinging on the test samples at approximately a 45° angle. his was attained by positioning a compressed air nozzle approximately seven inches from the paddle. To control rear surface cooling, foam was placed over the rear of the paddle. The paddle and foam backing were secured to an aluminum mounting plate. Foam was also placed over the lower front of the paddle. The laser was rastered over the end of the paddle, while the thermocouple outputs were recorded on an oscilloscope. Table 16 shows the actual strip parameters for the paddles.

4.1.11.1.4 Thermal data were taken with low-mass, type T, thermocouples, model C02-T by Omega Engineering. The copper-constantan junction tips are 0.0005 inch thick. The thermocouple output was amplified 247.3 times and cold-junction compensated to 0° C (32 °F) with an Analog Device AD565 thermocouple amplifier. This amplifier, although designed for type K thermocouples, compensates for type T thermocouples within 11 microvolts (which is correctable). The output voltage was converted to temperature according to NIST-traceable tables for 0 ° C referenced thermocouples. The thermocouple amplifier output was recorded with an H-P 54503A digitizing oscilloscope.

4.1.11.2 Panel testing - constant PRF.

4.1.11.2.1 Four of the phase lb test matrix panels were used for this phase of the test; table 14, B49 (fiberglass and epoxy) and B58, B59, and B60 (graphite composite). Twenty areas were stripped on each panel for four-point flexure testing. The airflow was set up the same as with the paddles to maintain consistency. The area to be stripped was placed in the central airflow. A thermocouple was placed on the back of the panel in the center of the area to be stripped in order to monitor the temperature rise. A small quantity of heat sink compound was applied to insure good thermal contact. A one-foot-square piece of foam was placed over the thermocouple and panel, then secured with an aluminum backing plate, to duplicate the conditions used for the paddle samples.

4.1.11.2.2 The PRF used on the full-size test panels was initially adjusted until a rear surface temperature was found that would produce the proper front surface temperature based on the previous paddle results. This PRF was then used for all of the graphite panels.

4.1.11.2.3 The graphite samples were stripped at a PRF = 0.03 Hz. Stripping the rain erosion coating at a fluence of 4.5 J/cm2 was found to be very time consuming. Therefore, through experimental trials, it was found that at a fluence of 6 J/cm2, a PRF of 0.24 Hz could be used, without overheating the substrate. Panel 59 (rain erosion coated graphite) was stripped at 6 J/cm2 0.24 Hz PRF until a thin layer was left. Then 4.5 J/cm2, 0.3 Hz was used for the remainder of the sample.

4.1.11.2.4 The graphite epoxy samples (B58, B59, and B60) required strip areas of 2" X 11/4'. Since a 0.3 PRF could not be achieved for such a large area, each strip area was divided into two sections.

4.1.11.2.5 The walkway coating thickness was very uneven, so the surface was sanded slightly to improve the uniformity of the coating removal. This was done on all of the areas stripped. Due to the composition of the walkway coating, it was necessary ~o periodically brush away the large inorganic particles left in the strip site. The composite reached thermal equilibrium after 14 raster patterns, so no brushing was performed until after equilibrium was reached. The strip parameters for the graphite epoxy substrates are included in tables 17- 19.

4.1.11.2.6 A simple computer model of the substrate heating was generated, and the results matched the experimental results for the graphite epoxy very well. Consequently, the model was used to select the PRF for the full-size fiberglass panels. Table 20 gives the strip parameters for the fiberglass panels.

4.1.11.2.7 There was a range of exposure levels for the four samples stripped for the second test. Sample B58 (table 18) was stripped exposing partial primer, partial substrate (on the composite peaks), and a thin coat of polyurethane topcoat. Sample 59B was stripped to a thin layer of topcoat, exposing a small amount of primer. The majority of B60 was stripped to expose the composite substrate, leaving primer in some areas, and walkway topcoat in others. This was to verify the material properties were not affected by the degree of stripping. The stripped panels were sent to Grumman for four point flexure testing per ASTM D790.

4.1.11.3 Panel testing - varying PRF. The set-up for this step was the same as before, except for airflow. After re-evaluating the feasible airflow for the final ALPS system, the set-up was modified to give a velocity of 50 feet/second.

4.1.11.3.1 With the first set of flexure tests for fiberglass panels, there appeared to be a slight reduction in flexure strength. Therefore, further samples were selected to determine the thermal damage threshold.

4.1.11.3.2 Tests were performed by varying the PRF for five sets of data with six samples per set at various temperature exposures [rear temperature ranging from 20 °C (68 ° E7) to 95 °C (203 °F)]. This was done to find the temperature at which the strength values begin to drop.

4.1.11.3.3 All samples were stripped at 15 Hz pulse repetition rate and a raster pattern size of 7 X 7 footprints. All samples in this step were stripped to the primer layer. The PRF was varied by manual timing using a stopwatch to attain PRFs of 0.025 Hz, 0.05 Hz, 0.066 Hz, and 0.312 Hz. All samples were taken from the same panel. A fluence of 4.5 J/cm2 was used to strip all sample areas. The stripping parameters are included in table 21.

4.1.11.4 Metallographic set-up. A section of each of the stripped panels was prepared for metallographic cross sectioning. The samples were cut from the panel and encapsulated in transparent resin. They were then ground and polished for metallographic examination.

4.1.12 Phase lb results.

4.1.12.1 Graphite epoxy paddle temperature rise testing.

4.1.12.1.1 The temperature profile for the front surface exhibited a distinct sawtooth pattern. The bulk temperature rose during the first eight to ten pulses and then stabilized. The rear surface temperature profile exhibited a slight ripple. The valleys in the front surface temperature profile were at approximately the same temperature as the rear surface. Also, after the paint was removed (approximately fifteen pulses), the temperature started to drop slightly.

4: 1.12.1.2 Four temperature measurements were taken off each thermal profile, which were the highest peak and valley temperature rise for both the front and rear surfaces. In most cases the measurement corresponded with the final laser pulse before the paint was removed. The temperature rise was then added to the starting temperature (i.e., room temperature of approximately 21 °C). For some samples, no data is reported because of thermocouple problems (table 16).

4.1.12.1.3 The temperature profile, through the thickness of the samples, was determined by graphing the difference between the maximum peak and valley temperature values. The temperature difference was graphed instead of the peak temperature to reduce possible experimental variations such as cooling air flow. There is a very steep temperature gradient in the first 0.001 inch below the surface. Although these results indicate that it is not practical to keep the surface of the substrate below 121 °C (250 °F), there is relatively little temperature drop between 0.002 inch below the surface and the rear surface. To estimate the peak temperature for a particular point in a graphite epoxy sample, the bulk sample temperature would have to be added to the temperature rise. For example, if the rear surface temperature was measured to be 80 °C (176 °F), the front surface peak temperature would be approximately 175 °C (315 °F) higher or 255 °C (491 °F).

4.1.12.1.4 The peak temperatures for the front and rear surfaces were graphed as a function of PRF. The temperature differential between the rear surface thermocouple and the 0.002inch-deep thermocouple ranged from 39 °C (70 °F) to 52 °C (94 °F). In the range where the front surface temperature was approximately 121 °C (250 °F), the front-to-rear surface temperature differential was 44 °C (79 °F). Under these conditions, the PRF that produced the front surface temperature of 121 °C (250 °F) was 0.5 Hz.

4.1.12.2 Graphite epoxy panel paint stripping.

4.1.12.2.1 The initial stripping on the full-size painted panels indicated that the PRF needed to be reduced from 0.5 Hz to 0.3 Hz. This was due to subtle changes in the cooling air flow. The graphite epoxy panel rear surface temperature rise measurements were recorded for each of the areas where four-point flexure test specimens were machined from the panels (tables 17 - 19). The front surface temperature estimates given on these tables were derived from a graph of peak temperatures measured at the rear surface and at 0.002 inch below the painted surface. Although the goal was to keep the average estimated front surface temperature below 121 °C (250 °F), the actual estimates turned out to be approximately 127 °C (260 °F) for samples B58 and B60 and 134 °C (273 °F) for sample B59. The length of time at elevated temperatures was generally about fifteen seconds. The length of time that any portion of a sample was above 121 °C (250 °F) was a small fraction of the 15 seconds.

4.1.12.2.3 The graphite epoxy four-point flexure test results are summarized in table 22 and presented in detail in table 23. A review of the average fracture stress values reveals that, with the exception of sample B58, the values for the stripped panels exceeded those of the control samples. Applying a single tailed student's T-test to determine if the lower fracture stress value for sample B58-tension is statistically significant, indicates that the difference is significant at the 97.5 % level. However, if the test is turned around, it indicates that, for three out of the remaining five test results, laser stripping increased the strength of the composite. In reality the differences observed are almost certainly due to normal variations in test data rather than due to the laser stripping process having altered the properties.

4.1.12.3 Fiberglass panel paint stripping.

4.1.12.3.1 The PRF used to strip the initial fiberglass epoxy samples was based on computer modeling of the temperature rise. The model predicted that, for a PRF of 0.25 Hz, the peak temperature would be 135 °C (275 °F) for the first pulse and 163 °C (325 °F) for the last. Since it did not appear that the 121 °C (250 °F) limit could be met at any rate based on this model, the fiberglass was stripped at a PRF of 0.2 Hz.

4.1.12.3.2 The fiberglass four-point flexure test results are summarized in table 24 and presented in detail in table 25. The average fracture stress for both tension and compression was slightly lower for the stripped samples than for the control samples but skill well within the variations observed for the graphite epoxy samples. Since the computer model indicated that the fiberglass epoxy was more prone to temperature rise and a limited number of samples was initially tested, additional samples were tested over a range of PRFs to establish if the previous testing was done close to a thermal damage threshold.

4.1.12.3.3 The second set of fiberglass flexure results is given in table 26. The rear surface temperatures observed in the initial fiberglass testing were approximately 70 °C (158 °F). For the second set of test results, the rear surface temperatures ranged from 40 °C (104 °F) to 110 °C (230 °F). It was anticipated that, within this range of temperatures, there would be a distinct decrease in flexural strength. However, none was apparent, indicating that the laser stripping process had not affected the properties.

4.1.12.4 Metallographic examination.

4.1.12.4.1 Examination of the metallographically prepared cross sections at magnifications up to 400X revealed no evidence of residual damage to the substrates. Even areas where the substrate was completely exposed revealed no evidence of resin removal. This is in contrast to the minor damage previously observed in samples that had been intentionally overstripped. The polyurethane-coated graphite epoxy sample (B58) had approximately 10% of the substrate exposed by the laser stripping process. The remainder of the surface consisted of exposed primer (approximately ten percent) and a thin layer of polyurethane. The remaining polyurethane was generally less than 0.001 inch thick. It was noted that the locations where the greatest amount of primer was removed corresponded to the high points on the surface of the substrate. It appeared that the primer did not completely level out the surface texture of the substrate while the topcoat did. This caused significant variations in the top coat thickness. A more rapid laser ablation rate for the primer would account for the thin or totally absent primer where the polyurethane had been removed.

4.1.12.4.2 The sample with rain erosion coating (B59) had a 0.001-inch-thick layer of topcoat remaining over the primer. There were isolated areas where the top coat was completely removed and the primer was removed almost down to the substrate. The samples with the walkway coating

(B60) had only a few isolated areas where topcoat remained (approximately 5%). Approximately 30% of the surface was completely exposed substrate. The remainder of the surface was covered with water-borne epoxy primer up to 0.001 inch thick.

4.1.12.4.3 The fiberglass epoxy sample with polyurethane topcoat (B49) had approximately 15% of the substrate surface exposed. Another 15% of the surface was exposed primer, while the remainder was covered with thin patches of polyurethane.

4.1.12.4.4 There was no correlation observed between the different amounts of substrate exposed during laser stripping and the flexure strength values.

4.1.13 Phase lb tests conclusions.

4.1.13.1 That graphite epoxy and fiberglass composites can be laser stripped without altering the properties was demonstrated. This was validated for rear surface peak temperatures up to 85 °C (185 °F).

4.1.13.2 Fiberglass epoxy composite is more sensitive to laser induced heating during laser paint stripping because of its lower thermal conductivity and lower specific heat.

4.1.13.3 Composite substrates can be exposed to several laser pulses during paint stripping without removal of resin from the matrix.

4.1.13.4 Although the very surface of the sample can reach temperatures as high as 255 ° C (491 °F), the temperature 0.002 inch below the surface does not exceed 135 °C (275 °F) for a rear surface temperature of 85 °C (185 °F) or lower.

4.1.13.5 It is feasible to strip composites at PRFs in the range of .02 to 0.3 Hz. It should be noted that the ALPS system was being designed to operate at a PRF of approximately 1.2 Hz.

4.1.14 Phase lb recommendations.

4.1.14.1 InTA recommended that the Navy proceed with the remaining phase lb test matrix. Stripping should be performed while monitoring the rear surface temperature rise to make sure it does not exceed 85 °C (185 °F).

4.1.14.2 Although the study fulfilled it goal of establishing a way of stripping composites without compromising the substrate properties, it did not answer the larger question of what are the effects of overheating due to excessive paint removal rates and under what conditions do they occur. This would require stripping a range of composite substrates and coatings at different rates in order to expose the substrate to a range of temperatures including those that caused significant property changes. The samples would then be subjected to ultrasonic inspection, four-point flexure testing, and metallographic cross sectioning. Such an effort was clearly beyond the scope of the existing ALPS phase I contract. InTA recommended that the existing contract be modified or a separate contract be issued to allow the proposed tests.

4.1.14.3 Subsequent to the phase lb test report from InTA, the Navy terminated the ALPS contract for convenience to the government.

4.2 AIR FORCE LADS PROGRAM.

4.2.1 LADS was procured and accepted as a turn-key, operational system.

4.2.1.1 LADS was developed in a well coordinated effort among a number of team players. The government effort was led by a representative from the Aircraft Division at Ogden Air Logistics Center. The overall system integrator was BDM Federal. BDM designed, built, and tested many of the individual subsystems, as well as directed the facility work at Hill AFB. Plasmatronics Inc. developed the pulsed CO_2 laser used.

4.2.1.2 Plasmatronics' 5 KW average power, rapid pulsed CO2 laser was introduced into the industrial setting at Hill Air Force Base as a turn key, operational tool in February 1995. The system was acceptance tested at Plasmatronics before delivery to the Air Force. The baseline LADS and its subsystems were designed specifically to decoat F-16 radomes.

4.2.1.3 Coating removal missions were examined in terms of special requirements or problem issues specific to each mission. Laser beam-material interaction mechanisms and how they apply to mission requirements were determined. In turn, a methodology was developed that achieved optimal laser induced coating removal performance for a wide variety of missions. In nearly all cases, a scenario can be found that offers near perfect selectivity, controllability, and zero substrate damage.

4.2.2 Coat removal scenario.

4.2.2.1Coating removal scenarios were developed for adapting the beam delivery subsystem to a wide variety of configurations and automation. Because of the laser beam characteristics, the control systems, and the system's flexibility a scenario can be developed to meet specific job requirements.

4.2.2.2 Case 1.

4.2.2.2.1 Coat and substrate are vastly differentiated by cold reflectivity R_i thermal conductivity k, and temperature sensitivity.

		<u>Reflectivity</u>	<u>K (w/cm^2°C)</u>	<u>T (°C)</u>
Coat -	Paint	5%	0.002	~ 400
Substrate -	Aluminum	~98%	2.04	660 (n)
	Iron	~95%	1.13	1535 (n3

<u>Paint on smooth aluminum:</u> Remove ~250 to 300 ft^2 mil/kWH, depending on paint
<u>Paint on smooth steel:</u> Remove ~250 to 300 ft2 mil/kWH, depending on paint
<u>Paint on textured iron:</u> Remove ~250 to 300 ft2 mil/kWH, bulk paint
<u>Paint buried in pores of textures:</u> Remove ~125 ft2 mil/kWH, subsurface

4.2.2.2.2 Comments about the case I scenario.

- Easiest Case - Power Density -25 kW/cm2 to S MW/cm2 OK for bulk ~100 kW/cm2 to 5 MW/cm2 Totally clean smooth metal surface ~1 MW/cm2 to 5 MW/cm2 Totally clean rough metal surface S 7.$ MW/cm2 to avoid acoustic damage

- J/Pulse ~ J/cm2, tp - 1 to 100 us bulk

- 1 to 10 1ls optimal at interface

- Relatively insensitive to beam profile

- Vision control feedback is not normally necessary

- Total cleaning with zero damage is easy

4.2.2.3 Case II.

4.2.2.3.1 Coat and substrate have similar properties (although substrate may be composite; example, polyurethane paint on fiberglass), and differentiate by reflectivity R_i, thermal conductivity, and temperature sensitivity.

		Reflectivity	K (w/cm^2°C)	T (°C)
Coat -	Paint	~ 5%	0.002	~ 400
	Primer	Similar	Similar	Similar
Substrate -	Resin	Similar	Similar	~ 400
	Fiberglass	Similar	0.0076	~ 800

4.2.2.3.2 Comments about the case II scenario.

- Requires moderately high peak power to provide clean, sharp interface.
  $\geq$ 2 200 kw/cm^2 provides ~ 0.0001" resolution.
  $\leq$ 5 mw/cm^2 avoids air breakdown tp ~ 1 to 5 usec optional
  ~ 5 J/cm^2 affords good efficiency

- Vision may be necessary to control penetration (can stop inside primer).

- Flat beam uniformity profile is highly desirable.

- Total cleaning with zero damage is readily achievable.

4.2.2.4 Case III.

4.2.2.4.1 Coat and substrate binder have similar properties (although substrate is a composite of vastly differing materials; example, polyurethane paint on carbon fiber/resin substrate), and differentiate by reflectivity R_i, thermal conductivity K, and temperature sensitivity.

		Reflectivity	K (w/cm^2°C)	T (°C)
Coat -	Paint	~ 5%	0.002	~ 400
	Primer	Similar	Similar	Similar
Substrate -	Resin	Similar	Similar	Similar
	Carbon Fiber	> 95%	0.02	3550

4.2.2.4.2 Comments about the case m scenario.

- Requires very high peak power to avoid cooking substrate binder via heat conduction through carbon fibers.

  ~ 1 to 5 MW/cm2 provides excellent interface boundary and good efficiency.
  Avoid > 5 MW/cm2 to prevent damage.
  ~5 Joules/cm2 provides best energy transfer without damage.
  tp ~ 1 to 5 usec.

- Carbon fiber substrate can be machined without damage using high flux density and low duty cycle.

- Residual fibers may protrude from substrate, but may be wiped off. Solid ~ strong surface remains.

- Beam uniformity and vision requirements are minimal.

- Total cleaning with zero damage is readily achievable.

4.2.3 Summary of F-4 and F-16 radome strip tests.

4.2.3.1 Parameters:

.
- Rep Rate: 100 pps
- Energy Density: SJoules/cm2
- Power Density: 4.2 Megawatts/cm
- Pulse Duration: 1.2 Microsecond
- Depth Removal/Pulse: 0.0004 inch (10 microns)
- Fraction of Spot Area Advance/Pulse: 22 %

4.2.3.2 Set Up:

- Vision and Feedback Control: Eye, manual control.
- Collection System: Transverse air sweep only.
- Manipulation: X-Y table moves sample in one axis. Beam moves in second axis.

4.2.3.3 Results:

- Fraction of coat strip: 100 %
- Damage: None
- Complication: Slight soot redeposition (wipes off with damp cloth).
- Strip rate:
  -- F-4: 276 ft2 mil/kWH 4 passes
  -- F-16: 265 ft2 mil/kWH 8 passes
  -- F-16: 248 ft2 mil/ kWH 9 passes - (needed to handle increased coat irregularity)

4.2.4 Conclusions.

4.2.4.1 Numerous diverse and important coat removal jobs have been theoretically analyzed; and a high energy laser has been developed to specifically meet the parameters identified in the study. A totally unique laser had to be developed to meet the requirements.

4.2.4.2 Optimal scenarios have been established and tested with the laser. In almost every case the following performances were achieved:

4.2.4.2.1 Complete removal of desired coat(s).

4.2.4.2.2 Damage-free substrate left intact; spatial resolution and depth control of ~ 0.0001" possible.

4.2.4.2.3 Complete recovery of removed coat byproducts. Basic chemical elements. (residue consists primarily of basic chemical elements.)

4.2.4.2.4 Compact removed coat byproducts without any added dilutants allows efficient storage (when contaminated impurities are involved).

4.2.4.3 The laser can be scaled and modified to meet any definable scaling requirement, i.e., tp is variable, and P_{max} > 200 kW is possible.

4.2.4.4 The laser is designed to be ultrareliable in all respects; > 109 shots MTBF is possible with routine maintenance.

4.3 ARMY ALPS PROGRAM.

4.3.1 The Army's ALPS system was procured as a turn-key operational system.

4.3.2 At the time of this publication CCAD had not accepted delivery of the system and the contractor had depleted the funds allocated for installing the system. The Army has some serious questions about the technology and future maintenance and repair costs.

4.3.2.1 The robot works well; however, the software developed for integration of the subsystems requires further refinements.

4.3.2.2 The system's strip rate is less than desired because of extra movement in the end effector head.

4.3.2.3 The system is experiencing smoke problems in the head and redesign is required.

APPENDIX I

JOINT POLICY COORDINATING GROUP ON DEPOT MAINTENANCE

TASKING DIRECTIVE 1-90

TASK THE JOINT TECHNOLOGY EXCHANGE GROUP TO CONDUCT A STUDY OF ALTERNATIVE PAINT REMOVAL PROCESSES W~CH HAVE POTENTIAL USE IN THE DEPOT MAINTENANCE COMMUNITY.

.
~EADOUARTERS US ARMY MATERIEL COMMAND y `< ~DEPUTY CHIEF OF NAVAL OPERATIONS :.- ~- :

5001 EISENHOWER AVE ALEXANDRlA VA 22333 0001 ~WASHINGTON DC 20350 ~30
DEPARTMENT OFTHE4IR FORCE DEPARTMENT OF THE AIR FORCE
HEADQUARTERS AIR FORCE LOGISTICS COMMAND HEADQUARTERS AIR FORCE SYS'EMS CO!'4!.';'~.

WRIGHT-PATTERSON AFB, OHIO 45433-5~1 ANDREWS AFB WASHINGTON DC 2~. ~:

Joint Policy Coordinating Group on
Depot Maintenance
(JPCC-DM)
Tasking Directive I - 90

TASK: The Joint Technology Exchange Group (JTEG) is tasked to conduct a study of alternative paint removal processes which have potential use within the DOD depot maintenance community, ensuring that selected alternatives are identified, given an appropriate evaluation, and that performance and developmental tests on individual processes are planned and conducted jointly by the Services to avoid duplication.

GENERAL GUIDANCE: The JTEG will plan and manage tI1e conduct of the study', identify the techniques to be studied, sponsor/advocate R&D initiatives, oversee joint Service testing, and evaluate and report the results

For the sake of expediency and possibility of realizing A fast return on this effort, the following paint removing processes will be studied first:

a. Sodium bicarbonate.

b. CO_2 pellets.

c Hi pressure H_2O.

d Laser.

e. PMB.

The test results from these processes could prove beneficial to Services that do not share the same specific processes as the Service performing the test

To reduce costs and timeframes, testing will be conducted at facilities that already have organic capability and will be supported by dedicated/selected personnel

SPECIFIC Guidance:

a. The JTEG will develop a study plan outlining objectives, milestones, and resource requirements for JPCG-DM approval

b The JTEG will plan and manage tile conduct of this joint Service study to include initiation and prioritization of study projects, and identification of resources required to conduct the study.

c. The JTEG will identify the techniques to be studied based upon joint Service needs and applicability to ensure those techniques with the greatest benefits are studied.

d. The JTEG Principals will advocate JPCG-DM coordinated R&D initiatives within their Service to ensure visibility, appropriate prioritization, and introduction to the Service R&D process.

e. JTEG will oversee joint Service evaluations to ensure that all appropriate product qualification testing, environmental testing, economic analysis and production feasibility analysis are accomplished.

f. JTEG will provide quarterly progress reports and a final report with recommendations for each removal process to the JPCG-DM.

g. The JTEG Principals .will be the focal point for identifying and coordinating their Service's activities relative to the study.

h. The JTEG Principals will ensure coordination with the Services' Product engineering authority on all test requirements relative to the study.

RESOURCES: The Services will provide the required resources (manpower, funding, facilities, equipment, etc.) as defined in the study plan. JTEG, as the overall study manager, will assist the Services in identifying and ensuring that resources that are already programmed for similar efforts are utilized to the maximum extent possible.

STUDY PLAN: The attached study plan is approved.

1 Atch
Study Plan

APPENDIX II

TABLES

TABLE 1
ALPS Phase la Test Matrix

ACTION	Matrix is for the number of samples

	A - Microhardness test performed if the temp.	
01 - Visual Inspection	rise experiments indicate that surface temp.	
02 - Surface Roughness	may have reached a level where material	
03 - Surface Cleanliness	properties could have been altered.	
04 - Paint		
05 - Visual Inspection	B - SEM-EDS analysis of anomalies performed	
06 - Paint Adhesion	only if corrosion products or other anomalies	
07 - Visual inspection	are observed that this technique could help	
08 - Machine Slots, Measure	to identify.	
Temperature Rise		
09 - Strip Paint	Inspection Responsibility	G Grumman
10 - Visual Inspection		I InTA
11 – Stereomicroscopic Inspection		
12 - Conductivity		
13 - Surface Roughness		
14 - Cut for Additional tests		
15 – Metallographic Cross-Section		
16 – Microhardness Tests		
17 - SEM-ED of Anomalies		
18 - Surface Analysis (SEM-EDS, Augar)		
19 - Tensile tests		

ACTION

	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
Responsibility	G	G	G	G	G	G	I	I	I	I	I	I	I	I	I	I	I	I	G
A1, 7075-76C.032"																			
1A-100C	1	1	-	-	-	-	1	-	-	-	1	1	1	1	2	A	B	1	3
1A-100-O	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	A	B	1	3
1A-100S	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	A	B	1	-
A1, 2024-T3C.032"																			
1A-200-C	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	A	B	1	3
1A-200-O	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	A	B	1	3
1A-200-S	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	A	B	1	-

A1, 2024-T3B.32"																			
1A-300-C	1	1	-	-	-	-	1	-	-	-	1	1	1	1	2	A	B	1	3
1A-300-O	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	A	B	1	3
LA-300-S	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	A	B	1	-

TABLE 1 (continued)

ACIION

	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
Responsibility	G	G	G	G	G	G	I	I	I	I	I	I	I	I	I	I	I	I	I
Fiberglass/Epoxy																			
(GM30(K)																			
1A-400-C	1	-	-	-	-	-	1	-	-	-	1	1	1	1	2	A	B	1	-
1A-400-O	1	-	-	1	1	-	1	1	1	1	1	-	-	1	2	-	B	1	-
1A-400-S	1	-	-	1	1	-	1	1	1	1	1	-	-	1	2	-	B	1	-
Carbon/Epoxy																			
(AS4/3501-6)																			
1A-500-C	1	-	-	-	-	-	1	-	-	-	1	-	-	1	2	-	B	1	-
1A500-O	1	-	-	1	1	1	1	1	1	1	1	-	-	1	2	-	B	1	-
1A500-S	1	-	-	1	1	-	1	1	1	1	1	-	-	1	2	-	B	1	-
Carbon/BMI																			
(HMF398/V378A)																			
1A-600C	1	-	-	-	-	-	1	-	-	-	1	-	-	1	2	-	B	1	-
1A-600-O	1	-	-	1	1	-	1	1	1	1	1	-	-	1	2	-	B	1	-
1A-600-S	1	-	-	1	1	-	1	1	1	1	1	-	-	1	2	-	B	1	-
Carbon/Epoxy																			
(HMF133/3501-6)																			
1A-700-C	1	-	-	-	-	-	1	-	-	-	1	-	-	1	2	-	B	1	-
1A-700-O	1	-	-	1	1	-	1	1	1	1	1	-	-	1	2	-	B	1	-
1A-700-S	1	-	-	1	1	1	1	1	1	1	1	-	-	1	2	-	B	1	-
Carbon/Epoxy																			
(IM6/3601-6)																			
1A-800-C	1	-	-	-	-	-	1	-	-	-	1	-	-	1	2	-	b	1	-
1A-800-O	1	-	-	1	1	1	1	1	1	1	1	-	-	1	2	-	B	1	-

TABLE 2

Pre-painting Surface Roughness Measurements

Sample No.	Ra Reading No. (Microinches)					Standard
	1	2	3	4	Mean	Deviation
1A-100 Vertical (against grain)	22.2	20.2	20.3	21.2	21.0	0.93
Horizontal	9.8	13.0	11.8	9.2	11.0	1.76

(with grain)						
1A-200 Vertical (against grain)	10.7	11.5	11.4	----	11.2	0.44
Horizontal (with grain)	9.5	9.3	10.3	----	9.7	0.53
1A-300 Vertical (against grain)	9.7	14.5	10.2	8.6	10.8	2.59
Horizontal	9.3	8.3	8.1	8.5	8.6	0.53

TABLE 3

Post-stripping Surface Roughness Measurements

Sample No.	Ra Reading No. (Microinches)						Standard
	1	2	3	4	5	Mean	Deviation
lA-lO-C	34	46	35	19	21	31.0	11.1
lA-100-S	10	12	11	12	10	11.0	1.0
lA-100-O	18	12	11	21	14	15.2	4.2
lA-200-C	12	13	12	12	13	12.4	0.5
1A-200-S	13	13	14	12	11	12.6	1.1
1A-200-O	14	22	13	12	15	15.2	4.0
lA-300-C	25	19	26	36	54	32.0	13.7
1A-300-S	48	53	44	43	50	47.6	4.2
1A-300-O	64	65	46	52	44	54.2	9.9

TABLE 4
Conductivity Measurements

	Low	High	Average
Sample No.	(ohms)	(ohms)	(ohms)
lA-100-C	2M	>20M	>20M
lA-100-S	SK	20K	12K
lA-100-O	SK	15E	lOK
1A-200-C	5M	>20M	>20M
lA-200-S	7K	50K	15K
lA-200-O	4K	15K	7K
lA-300-C	20M	>20M	>20M
lA-300-S	500	7K	3K
lA-300-O	500	lOK	2K

TABLE 5
Metallographic (Cross Section Thickness Results

Sample No.	Substrate Thickness *(inch)	Paint Thickness (inch)
A-400-C	0.034	0.005 - 0.006
lA~S	0.035	
lA-400-O	0.036	
lA-500-C	0.075	0.011 - 0.013
lA-500-S	0.080	
1A-500-O	0.079	
1A-600-C	0.029	0.005 - 0.008
lA-600-S	0.029	
lA-600-O	0.029	
lA-700-C	0.034	0.005 - 0.006
1A-700 S	0.043	
lA-700-O	0.042	
lA-800-C	0.091	0.008 - 0.011
lA-800-S	0.091	
lA-800-O	0.094	

*Average of Six Measurements

TABLE 6

Static Tensile Properties (Control and Overexposure) of 1A-200 and IA-300 Specimen

Property	Controls		Overexposure	
	1A-300	1A-200	1A-300	1A-200
F_{tu} (ksi)	71.0	64.7	0.3	64.6
	71.1	64.7	69.2	65.1
	71.7	64.7	70.1	62.4
Average:	71.3 ± .38	64.7 ± 0.0	69.5 ± .49	64.0 i 1.44
"B" Basis	65.0	61.0	~	
F_{ty} (ksi)	56.6	50.6	58.2	51.0
	56.6	50.6	58.0	51.4
	56.6	50.6	S7.3	49.3
Average:	56.6 ± 0.0	50.6 ± 0.0	57.8 ± .47	S0.6 i 1.12
"B" Basis	48.0	45.0		
S_f (ksi)	86.2	78.5	78.0	78.1
	84.2	78.8	80.5	79.6
	90.8	78.8	82.3	78.5
Average	87.1 ± 3.38	78.7 ±: .17	80.3 ± 2.16	78.7 :±: .78
E (ksi)	10,100	9,750	10,600	9,800
	10,400	9,920	10,200	9,300
	10,500	10,300	10,000	9,400
Average	10,333 ± 208	9,990 ± 282	10,267 ± 306	9,500 + 265
elong. (%)	15.5	17.0	11.0	14.0
	15.5	17.0	10.0	14.5

	15.5	14.0	12.5	14.5
Average:	15.5 ± 0.0	16.0 ± 1.73	11.2 ± 1.26	14.3 ± 29
% RA	18.8	18.8	16.4	18.8
	18.8	18.8	17.4	18.8
	20.0	18.8	18.4	18.8
Average:	19.2±.69	18.8 ± 0.0	17.4+ 1.0	18.8± 0.0

Note: (1) All overexposed (1A-200-0) specimens failed away from centerline.

TABLE 7
Static Tensile Properties (Contm1 and Overexposed) of lA- 100 Specimen

Property	Contro1	Overexposed
F_{tu} (ksi)	77.5	77 8
	78.4	77.8(1)
	78.1	77.5
Average:	78.0	77.7 ± .21
"B" Basos	73.0	--
F_{ty} (ksi)	71.0	71.3
	71.3	71.3
Average:	71.2 ± .17	71.3 ± 0.0
"B" Basis	65.0	--
S_f (ksi)	98.3	94.6
	96.4	88.6(1)
	99.6	93.8
Average:	98.1 ± 1.61	94.2 ± .57
E (ksi)	9,500	9,620
	9,400	9,660
Average:	9,433 ± 58	9,640 ± 28
elong. (%)	12.0	11.5
	13.5	6.0(1)
	13.5	12.0
Averagc:	13.0 ± .87	11.75 ± .35
% RA	22.7	18.8
	22.0	12.5(1)
Average:	22.9 ± 1.07	18.8 ± 0.0

Note: (1) One of three overexposed specimens failed away from centerline, at a punch mark' and is not included in dle average properties shown.

TABLE 8
ALPS Phase Ia Supplemental Test Matrix

ACTION		
01 Visual Inspection	06 Visual Inspection	11 Surface Roughness
02 Surface Roughness	07 Machine Slots,	12 Laser Parameter Testing
03 Surface Cleanliness	Measure Temperature	13 Metallographic

Testing	08 Strip Paint	Cross-Sections
04 Paint	09 Visual Inspection	14 Surface Analysis
05 Paint Adhesion	10 Tensile Testing	(SEM-EDS)

Action

		01	02	03	04	05	06	07	08	09	10	11	12	13	14
Aluminum	1A-100-C	1	-	-	-	-	-	-	-	-	3	-	-	-	
7075-T6C,032"	1A-100-O	1	1	1	1	1	1	-	1	1	3	1	-	-	-
	1A-100-S	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Aluminum,	1A-200-C	1	-	-	-	-	-	-	-	-	-	-1	-	-	-
2024-T3C.032"	1A-200-C	1	1	1	1	1	1	8	1	1	3	1	5	1	5
	1A-200-O	1	1	1	1	1	1	8	1	1	3	1	5	1	5
	1A-200-S	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Aluminum,	1A-300-C	1	-	-	-	-	-	-	-	-	C	-	-	-	-
2024-T3B.032"	1A-300-O	1	1	1	1	1	1	8	1	1	3	1	5	1	5
	1a-300-S	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fiberglass/Epoxy	1A-400-C	-	-	-	-	-	-	-	-	-	-	-	-	-	-
(GM3006)	1A-400-C	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	1A-400-S	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Carbon/Epoxy	1A-500-C	-	-	-	-	-	-	-	-	-	-	-	-	-	-
(AS4/3501-6)	1A-500-O	1	-	-	1	1	1	8	-	-	-	-	-	-	-
	1A-500-S	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Carbon/BMI	1A-600-C	-	-	-	-	-	-	-	-	-	-	-	-	-	-
(HMF398/V378A)	1A-600-O	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	1A-600-S	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Carbon/Epoxy	1A-700-C	-	-	-	-	-	-	-	-	-	-	-	-	-	-
(HMF133/3501-6)	1A-700-O	1	-	-	1	1	1	8	-	-	-	-	-	-	-
	1A-700-S	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Carbon/Expoxy	1A-800-C	-	-	-	-	-	-	-	-	-	-	-	-	-	-
(IM6/3501-6)	1A-800-O	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	1A-800-S	-	-	-	-	-	-	-	-	-	-	-	-	-	-

TABLE 9.
Average Roughness Measurements in Microinches

Before Stripping	Single-strip	Over-strip
lA-lXX-X mean 23.4	58.6	58.4
standard dev. 3.0	1.5	4.0
lA-2XX-X	mean 24.1 61.0	44.0
standard dec.	1.9 7.4	1.6
lA-3XX-X mean 16.6	33.6	68.6
standard dev. 4.3	3.8	3.2

* Each value is an average of a minimim of five measurements.

TABLE 10.
Tensile Test Results, Clad 7075-T6

	Requirement	Control *	Over-strip
	MIL-HDB-SD	lA-101-C	lA-102-O
Tensile	73,000	75,700	77,100
Strength	(B Basis)	77,400	77,100
(psi)		77 400	77,600
		74,000	77,000
		77,800	77,000
mean		76,460	77,160
std. dev.		1,428	224
Yield	65,000	68,600	66,900
Strength	(B Basis)	68,200	66,500
(psi)		68,500	67,100
		66,900	67,400
		66,000	67,900
mean	67,640	67,160	
std. dev.	1,021	*n2*	
True	none	97,100	105,900
Fracture	102,600	99,500	
Stress	98,200	106,300	
(psi)	94,100	99,300	
		96,100	97,300
mean		67,620	101,660
std dev.		2,832	3,708
Reduction	none	- 22.0	27.2
in area		24.6	22.5
(%)		21.2	27.0
		21.	22.5
		24.	20.8
mean		22.7	24.0
std. dev.		1.S	2.6
Modulus	10.3	9.8	9.3
(1000 ksi)	(Primary)	10.6	9.4
		10.7	9.4
	9.5	9.6	9.5
	(Secondary)	10.5	9.5
mean		10.2	9.4
std. dev.		0.4	0.1
Elong. (%)	none	6.5 *	13.5
		9.0*	13.5
		8.0*	13.5
		5.0 *	13.5
		5.0 *	13.Q

mean	6.7 *	13.4
std. dev.	1.6	0.2

* Note: All of the lA-101-C tensile samples fractured at the very edge of the reduced section. This produced abnonnally low elongation values.

TABLE 11.
Tensile Test Results, Clad 2024-T3

	Requirement	Control	Over-strip
	MIL~HD8K-SD	lA-201-C	lA-202-O
Tensile	61,000	66,300	65,600
Strength	(B Basis)	66,300	66,300
(psi)		67,000	66,300
		66,500	65,800
		67,200	65,600
mean		66,660	65,920
std dev.		372	319
Yield	45,000	47,700	44,500
Strength	(B Basis)	47,300	46,400
(psi)		47,700	44,400
		46,700	45,700
		48,000	44,900
mean		47,480	45,180
std. dev.		449	763
True	none	88,200	87,900
Fracture		86,900	86,100
Stress		88,700	84,100
(psi)		86,900	85,000
		85,900	89,900
mean		87,320	86,600
std. dev.		1,005	2,080
Reduction	none	24.8	25.3
in area		23.7	23.0
(%)		24.5	21.0
		23.5	22.5
		21.8	27.0
mean		23.7	23.8
std. dev.		1.0	2.1
Modulus	10.5	11.0	10.8
(1000 ksi)	(Primary)	10.8	11.0
		10.9	10.1
	9.5	11.3	10.7
	(Secondary)	9.8	11.1
mean		10.8	10.7
std. dev.		0.5	0.9

Elong. (%)	none	178 55	18 0
		16.0	17.5
		17.5	19.0
		17.0	18.5
mean		17.3	17.9
std. dev.		0.8	0.9

TABLE 12.
Tensile Test Results, Bare 2024-T3

	Requirement	Control	Over-strip
	MIL-HDBK-5D	lA-301-C	lA-302-O
Tensile	65,000	69,000	67,900
Strength	(B Basis)	68,000	67,200
(psi)		68,000	67,600
		68,200	67,600
		68,100	67,300
mean		68,260	67,520
std. dev.		377	248
Yield	48,100	48,100	47,700
Strength	(B Basis)	48,800	45,900
(psi)		48,800	47,100
		49,300	46,400
		47,600	47,500
mean		48,520	46,920
std. dev.		598	676
True	none	88,700	90,400
Fracture		87,900	88,900
Stress		89,900	86,600
(psi)		90,600	89,600
		89,600	87,200
mean		89,340	88,540
std. dev.		944	1,433
Reduction	none	22.2	24.9
in area		22.7	24.5
(%)		24.3	21.9
		24.8	24.6
		24.0	22.8
		:	
mean		23.6	23.7
sed. dev.		1.0	1.2
Modulus	10.5	10.6	11.1
(1000 ksi)		10.5	10.8
		10.7	11.3
		11.0	11.2
		1 1.0	10.9
mean		10.8	11.1

std. dev.		0.2	0.2
Elongation (%) none		13.5	17.0
		16.5	18.0
		18.0	18.0
		16.5	17.0
		17.0	19.0
mean		16.3	17.8
std. dev.		1.5	0.7

TABLE 13.
Aluminum Temperature Rise Above Ambient for
Single Strip (approximately 14 pulses)

Sample	Depth	Temperature (°F)
Clad		
1A-202-4	0.0005	X
1A-202-2	0.001	84
1A-202-3	0.0015	94
1A-202-5	0.0025	X
1A-202-1	0.0035	106
Unclad		
1A-302-4	0.0005	101
1A-302-2	0.001	99
1A-302-3	00015	113
1A-302-6	0.0025	X
1A-302-1	0.0035	111

TABLE 14.

Sample Numbers for Phase Ib Single Strip and Four Cycle Testiing.

Coatings					
	PS				FP
	EP	KOR	EP	WBEP	CARC
Substrate	PU	PU	RAIN	WALK	EG
One strip cycle					
Metal (1' X 3")					
7075-T6C, 0.016"	Bl	B2	B3	B4	-
7075-T6B 0.063"	B5	B6	B7	B8	-
2024-T3B 0.016"	B9	Bl0	Bll	Bl2	-
2024-T3C, 0.063.'	Bl3	Bl4	Bl5	Bl6	-
2024-T81C, 0.032"	Bl7	Bl8	Bl98	B20	-
2024-T81B, 0.032"	B21	B22	B23	B24	-
T1-6AI.-4V,0.03"	B25	B26	B27	B28	-
T1 6-6-2, 0.030	B29	B30	B31	B32	-
D6AC STEEL, 0,187"", NO PRETREAT	B33	B34	B35	B36	-
D6AC STEEL, 0.187", GRIND & CAD PLATE	B37	B38	B39	B40	-
17-7PH THI050 SS	B41	B42	B43	B44	-
METAL-METAL	B45	B46	B47	B48	-

Composite (1' X 3')					
FIBERGLASS/EPOXY (GM4C01-G42)	-	B49	B50	B51	-
GRAPHITE/EPOXY (AS4 TAPE, 3501-6	-	B52	B53	B54	-
GRAPHITE BMI (AS4, V378A)	-	B55	B56	B57	-
GRAPHITE (AS4, 3501-1)	-	B58	B59	B60	-
GRAPHITE (IM6 TAPE, 3501-6)	-	B61	B62	B63	-
KEVLAR 49/EPOXY	-	-	-	-	B64
Four stryp cycles					
Metal (1'X4')					
7075-T6C, 0.016"	Cl	C2	C3	C4	-
7075-T6B, 0.063"	C5	C6	C7	C8	-
2024-T3B, 0.016"	C9	C10	C11	C12	-
2024-T3C, 0.063"	C13	C14	C15	C16	-
2024-T81C, 0.032"	C17	C18	C19	C20	-
2024-T81B, 0.032	C21	C22	C23	C24	-
TI-6AL-4V, 0.030"	C25	C26	C27	C28	-
TI 6-6-2, 0.030"	C29	C30	C31	C32	-
D6ACSTEEL, 0.187", NO PRETREAT	C33	C34	C35	C36	-
D6ACSTEEL, 0.187", GRIND & CAD PLATE	C37	C38	C39	C40	-
17-7PH TH1050 SS	C41	C42	C43	C44	-
METAL-METAL	C45	C46	C47	C48	-
Composite (1' X 3')					
FIBERGLASS/EPOXY (GM4C01-G42)	-	C49	C50	C51	-
GRAPHITE/EPOXY (AS4 TAPE, 3501-6)	-	C52	C53	C54	-
GRAPHITE BMI(AS4 V378A)	-	CSS	CS6	C57	-
GRAPHITE (AS4,3501-6)	-	C58	C59	C60	-
GRAPHITE (IM6 TAPE, 3501-6)	-	C61	C62	C63	-
KEVLAR 49/EPOXY	-	-	-	-	C64
Special testing					
(Overexposed)					
2024-T3C, 0.063"	-	Al	-	-	-
GRAPHITE/EPOXY (AS4, 3501-6)	-	A29	-	-	-
17-7PH THI050 SS	-	A3	-	-	-
(One strip cycle)					
7075-T6B, 0.063" RIVETED	-	A4	-	-	-
TOTALS	24	39	34	34	2

PS = POLYSULFIDE SEALER
EP = EPOXY PRLUBR
PU = POLYURETHANE TOPCOAT
KPR= = KOROFLEX PRIMER
WBEP = WATER BORNE EPOXY PRIMER
WALK = WALKWAY COATING
RAIN = RAIN EROSION COATING
CARC = CHEMICAL AGENT RESISTANT COATING
EG = EROSION GUARD (POLYURETHANE/ADHESIVE)

TABLE 15.

Paddle Sample Thickness and Depth of Thermocouple Near the Front Surface.

		Front Surface
Paddle Sample	Paddle Thickness	T/C Depth
001	35 mil	.002"
002	35 mi1	.002"
003	35 mil	.002"
004	81 mil	.002”
005	81 mil	.002"
006	43 mil	.002"
007	43 mil	.002"
008	43 mil	.002"
009	43 mil	.002"
010	43 mil	.002"
011	43 mil	.002"
012	43 mil	.002"
013	43 mil	.002"
014	43 mil	.002"
015	43 mil	.002"
016	43 mil	.002"
017	43 mil	.002"
018	43 mil	.002"
019	43 mil	.004"
020	43 mil	.008"
021	43 mil	.000"
022	43 mil	.000"
023	43 mil	.000"
024	43 mil	.000"

TABLE 16.

Paddle Sample Test Parameters and Results.

		Depth (from		Maximum Peak		Maximum Valley	
Sample	Thickness	front surface)	PRP	Temperature(°C)		Temperature(°C)	
Number	(inch)	(inch)	(Hz)	Front	Rear	Front	Rear
2	.035	.002	.51	115	--	77	--
4	.081	.002	.50	101	64	78	--
5	.081	.002	.74	133	69	97	69
7	.043	.002	.50	118	--	82	--
8	.043	.002	.50	108	74	78	72
9	.043	.002	.75	128	89	111	89
10	.043	.002	.50	113	--	85	--
11	.043	.002	.33	105	--	72	--
12	.043	.002	.25	90	52	56	50
13	.043	.002	1.11	142	84	112	82

14	.043	.002	.50	126	87	86	82
15	.043	.002	.50	113	68	88	65
17	.043	.002	.33	105	65	72	60
18	.043	.004	.50	119	--	97	--
19	.043	.008	.51	121	--	102	--
21	.043	.000	.30	219	--	52	--
22	.043	.000	.30	233	--	47	--
23	.043	.000	.30	258	--	51	--
24	.043	.000	.30	205	--	52	--

TABLE 17.
Polyurethane Coated Graphite Epexy (Sample B58) Strip Parameters, Rear Surface Temperature Rise Measurements and Peak Temperature Estimates for 0.002 inch Below the Pront Surface.

Sample #/Section	Pattern Size (X x Y)	Laser Rate (Hz)	PRF (Hz)	T_{room} (°C)	ΔT_{rear} (°C)	T_{front} (°C)
1/1	10 x 4	12	0.3	19	46	104
1/2	10 x 4	12	0.3	19	47	105
2/1	5 x 7	10.5	0.3	21	63	132
2/2	5 x 7	l0.S	0.3	21	61	129
3/1	10 x 4	12	0.3	21	61.5	130
3/2	10 x 4	12	0.3	21	37	93
4/1	10 x 4	12	0.3	21	62	132
4/2	10 x 4	12	0.3	21	48	110
5/1	10 x 4	12	0.3	21	59	126
5/2 (thermocoupe broke)		--	--	--	--	--
6/1	10 x 4	12	0.3	19	58	122
6/2	l0 x 4	12	0.3	19	49	109
7/1	10 x 4	12	0.3	19	S5	117
7/2	l0 x 4	12	0.3	19.5	49	110
8/1	5 x 7	10.5	0.3	20	68	139
8/2	5 x 7	10.5	0.3	21	61	128
9/1	5 x 7	10.5	0.3	21	68	140
9/2	5 x 7	10.5	0.3	20.5	60	128
10/1	5 x 7	10.5	0.3	20	66	134
10/2	5 x 7	10.5	0.3	20	59	125
11/1	5 x 7	10.5	0.3	21	67	139
11/2	5 x 7	10.5	0.3	21	56	121
l2/1	5 x 7	10.5	0.3	20.5	67	138
12/2	5 x 7	10.5	0.3	24.5	63	133
13/1	5 x 7	10.5	0.3	20	58.5	124
13/2	5 x 7	10.5	0.3	21	54	119
14/1	5 x 7	10.5	0.3	21	63.5	134
14/2	5 x 7	10.5	0.3	20.5	63.5	132

15/1	5 x 7	10.5	0.3	21.5	61	130
15/2	5 x 7	10.5	0.3	20.5	64	133
16/1	5 x 7	10.5	0.3	20.S	65	134
16/2	5 x 7	10.5	0.3	20	63	130
17/1	5 x 7	10.5	0.3	20	67.5	138
17/2	5 x 7	10.5	0.3	21	59	126
18/1	5 x 7	10.5	0.3	20.5	68	140
18/2	5 x 7	10.5	0.3	20	61.5	129
9/1	5 x 7	10.5	0.3	20.S	61.S	129
19/2	5 x 7	10.5	0.3	21	59.S	127
20/1	5 x 7	10.5	0.3	20.5	62.5	131
20/2	5 x 7	10.5	0.3	20.5	61	129

TABLE 18.
Rain Erosion Coated Graphite Epoxy (Sample B59) Strip Parameters,
Rear Surface Temperature Rise Measurements and Peak Temperature Estimates for
0 002 inch Below the Front Surface.

For all Samples the Pattern Size (X x Y) = 5 x 7 and the PRF (Hz) = 0.3

	T_{room}	ΔT_{rear}	T_{front}
Sample/Section	(°C)	(°C)	(°C)
1/1	20	75	150
1/2	20	61.5	129
2/1	20	67.5	138
2/2	18.5	60	125
3/1	18.5	67.5	135
4/2	19.5	61.5	128
5/1	20	67	136
6/2	22	64.5	136
7/2	23	58.5	115
8/1	24	66	142
9/2	20	83	160
10/2	19.5	61.5	128
11/1	19.5	73	148
l21	19	69	139
13/2	19.5	65	133
14/1	19.5	64	131
l5/1	19.5	64	131
16/2	21	55	120
17/1	20	66	134
18/2	20.5	58.5	125
19/1	20	64	131
20	20.5	65	132

TABLE 19.
Walkway Coated Graphite Epoxy (sample B60) Strip Parameters,
Rear Surface Temperature Rise Measurements and Peak Temperature Estimates for
0.002 inch Below the Front Surface.
For all samples the pattern size (X x Y) = 5 x 7 and the PRF (Hz) = 0.3.

	T_{room}	ΔT_{rear}	T_{front}
Sample/Section	(°C)	(°C)	(°C)
1/1	20	63	130
1/2	20.5	60	127
2/1	20.5	56	121
2/2	20.5	61	129
3/2	20.5	61	129
4/1	20	56	121
11/1	19	62	128
12/2	19	60.s	127
13/1	19	62.5	130
14/2	19	62	128
15/1	19	66	133
16/1	20	60.s	127
7/2	19	59.5	124
18/2 (Bad connection)	--	--	--
19/1	19	60.5	126

TABLE 20.
Polyurethane Coatod Fiberglass (Sample B49) Strip Parameters, and
Rear Surface Temperature Rise Measurements.

	Laser Rate	Pattern Size	PRF	Room	Δ_{rear}
Sample #	(Hz)	(XxY)	(Hz)	Temp. (°C]	(°C)
1	9	6 x 6	.2s	19.5	56.5
2	lQ5	7 x 6	.25	21.0	61.5
3	12.5	7 x 7	.25	21.5	62.0
4	10.5	6 x 7	.25	22.0	72.0
5	9	6 x 6	.25	22.0	52.0
6	10.5	6 x 7	.25	21	50.5
7	10.5	6 x 7	.25	21.5	50.5
8	10.5	6 x 7	.25	22.0	52.0
9	10.5	6 x 7	.25	22.5	45
10	8A	6 x 7	.20	18.5	44

11	9.8	7x7	.20	19.5	44
12	9.8	7 x 7	.20	19.5	43.5
13	9.8	7 x 7	.20	19.0	46.s
14	9.8	7 x 7	.20	19.5	50
15	9.8	7 x 7	.20	18.5	32*
16	9.8	7 x 7	.20	19.0	49
17	9.8	7 x 7	.20	18.5	44
18	9.8	7 x 7	.20	18.5	42.5
19	9.8	7 x 7	.20	18.5	43.5
20	9.8	7 x 7	.20	19.5	44

TABLE 21.
Strip Parameters and Rear Surface Temperature Rise Measurements for
the Second Set of Polyurethane Coated F~berglass Samples.

Sample	PRF (Hz)	T_{room} (°C)	T_{rear} (°C)	Sample	PRF (Hz)	T_{room} (°C)	T_{rear} (°C)
A1	.025	21	42.5	D1	.208	21	89
A2	.025	21	43.5	D2	.161	21	87.5
A3	.033	23	49	D3	.13	21	75
A4	.025	21	45.5	D4	.161	21	84.5
A5	.025	21	42.5	D5	.161	21	82.5
A6	.025	21	42.5	D6	.161	21	82.5
B1	.066	21	57	E1	.05	21	51.5
B2	.066	21	62	E2	.05	21	52.5
B3	.066	21	61	E3	.05	21	52
B4	.066	21	62.5	E4	.05	21	52
B5	.066	21	61	E5	.05	21	52
B6	.066	21	57	E6	.033	21	48
C1	.332	21	116	X1	NA	21	21
C2	.312	21	116	X2	NA	21	21
C3	.294	21	105	X3	NA	21	21
C4	.312	21	106	X4	NA	21	21
C5	.312	21	105	X5	NA	21	21
C6	.312	21	103	X6	NA	21	21

TABLE 22.
Four-point Flexure Test Results Summary for Graphite Epoxy Samples.
('Ihe detail results are given in table 23)

			Stress		Modulus	
Coating	Number	Orientation	Mean	Std. Dev.	Mean	Std. Dev
None	15	tension	179.5	4.3	9.37	0.31
(control)		compression	176.8	7.9	9.79	0.17
Polyurethane	B58	tension	186.9	8.9	9.46	0.39
		compression	183.8	4.0	9.37	0.12
Rain	B59	tension	174.6	5.3	8.85	0.18
Erosion		compression	182.6	5.2	8.87	0.22
Walkway	B60	tension	186.3	4.5	9.85	0.27
		compression	176.6	4.1	9.50	0.23

TABLE 23.
Four-point Flexure Results.

Unpainted Graphite Epoxy, Sample 15,
AS4, 3501-6, Fabric (control sample); suppon span = 1.34 inch; none. thick. = 0.040 inch.

				Stress		Modulus	
	Thickness	Width	Load	Actual	Normalized	Actual	Normalized
Speciman	(inch)	(inch)	(LB)	(ksi)	(ksi))	(msi)	(msi)
side in tension							
1	0.043	1.002	306	166	178	8.7	9.4
2	0.043	1.003	310	168	181	8.9	9.6
3	0.042	0.999	310	177	186	9.3	9.8
4	0.042	0.999	300	171	180	9.3	9.8
5	0.042	1.005	313	177	186	8.8	9.2
6	0.042	0.994	302	173	182	9.0	9.5
7	0.042	1.002	292	166	174	9.0	9.5
8	0.042	1.003	300	170	179	8.8	9.2
9	0.041	1.000	285	170	175	8.9	9.1
10	0.042	0.999					
Mean	0.042			170.6	179.5	8.90	9.37
std. dev.	0.001			4.2	4.3	0.29	0.31
side in compression							
11	0.042	0.999	264	151	158	8.9	9.3
12	0.042	0.999	294	168	176	9.4	9.9
13	0.041	1.003	300	179	183	9.6	9.8
14	0.041	1.003	287	171	175	9.7	9.9
15	0.042	1.004	298	169	178	9.3	9.8
16	0.041	l.OQ4	290	173	177	9.7	9.9
17	0.043	1.003	300	163	175	9.1	9.8
18	0.042	0.999	298	170	178	9.4	9.9
19	0.042	1.005	318	180	189	9.3	9.8
20	0.043	0.999	304	165	178	9.1	9.8
mean	0.042	168.8	176.8	9.3S	9.79		
std. dev.	0.001	8A	79	0.27	0.17		

Polyurethane Coated Graphite Epoxy, Sample B58; AS4,3501-6 Fabric w/Koroflex, Polymethane; support span = 1.34 inch; norm. thiclc. = 0.040 inch. stripped side in tension

1	0043	1.001	309	168	180	8.2	8.8
2	0.043	1.002	329	178	192	8.5	9.1
3	0.043	1.002	330	179	192	8.7	9.4
4	0.043	1.001	308	167	180	8.7	9.4
5	0.044	1.002	305	158	174	8.4	9.2
6	0.044	1.002	337	175	192	8.6	9.5
7	0.045	1.002	316	157	176	8.6	9.7
8	0.041	1.001	327	195	200	10.0	10.3
9	0 044	0.997	325	169	186	89	9.8
10	0 042	1.002	328	186	196	9.1	9.6
mean	0.043			173.3	186.9	8.77	9.46
std. dev.	0.001			12.1	8.9	0.50	0.39

TABLE 23. (Continued)

				Stress		Modulus	
	Thickness	Width	Load	Actual	Normanlized	Actual	Normalized
Speciman	(inch)	(inch)	(LB)	(ksi)	(ksi)	(msi)	(msi)
Stripped side in compression							
11	0.042	1.001	311	177	186	9.0	9.5
12	0.042	0.999	320	182	192	9.1	9.6
13	0.043	1.001	319	173	186	8.7	9.4
14	0.043	0.999	306	166	179	8.7	9.4
15	0.043	0.999	305	166	178	8.6	9.2
16	0.044	1.001	315	163	180	8.4	9.2
17	0.044	1.000	322	167	184	8.4	9.2
18	0.043	1.001	314	171	183	8.7	9A
19	0.043	1.002	319	173	186	8.9	9.6
20	0.043	1.000	315	171	184	8.7	9.4
mean	0.043			171.0	183.8	8.72	9.37
std. dev.	0.001			5.7	5.7	0.23	0.12
Rain Erosion Coated Graphite Epoxy; Sample B59 AS4, 3501-6 Fabric w/Epoxy; Support span = 1.34 inch; Normal Thickness = 0.040 inch. Stripped side in tension							
1	0.042	1.000	276	157	165	8.3	8.7
2	0.043	1.003	293	159	171	8.1	8.7
3	0.043	0.999	294	160	172	8.0	8.6
4	0.042	1.000	290	165	173	8.6	9.0
5	0.044	1.001	308	160	176	7.9	8.7
6	0.044	0.999	297	154	170	8.0	8.8
7	0.044	1.001	317	164	181	8.2	9.0
8	0.044	0.996	308	168	181	8.5	9.1
9	0.044	1.001	315	163	180	8.1	8.9
10	0.044	0.999	311	162	178	8.1	8.9

mean	0.043			161.3	174.6	8.18	8.85
std. dev.	0.001			4.1	5.3	0.23	0.18
Stripped side in compression							
11	0.043	1.002	322	175	188	8.5	9.1
12	0.043	0.999	316	172	185	8.5	9.1
13	0.044	1.001	300	156	171	8.0	8.8
14	0.043	0.999	309	168	181	8.3	8.9
15	0.043	1.000	318	173	186	8.3	8.9
16	0.044	0.999	314	163	179	7.9	8.7
17	0.043	0.998	315	172	184	7.9	8.5
18	0.042	0.999	304	173	182	8.5	8.9
19	0.042	1.001	302	172	180	8.2	8.6
20	0.041	0.997	308	185	189	8.8	9.0
mean	0.043			170/8	182.6	8.92	8.87
std. dev.	0.001			7.6	5.2	0.30	0.22

TABLE 23. (Continued)

Walkway Coated Graphite Epoxy; Sample B60;
AS4 3501-6 Fabric w/Water Borne Epoxy; Suppart span = 1.34 inch; Nonnal ll~ickness = 0.040 inch.

				Stress		Modulus	
	Thickness	Width	Load	Actual	Normalized	Actual	Normalized
<u>Speciman</u>	(inch)	(inch)	(LB)	(ksi)	(ksi)	(msi)	(msi)
Stripped side in tension							
1	0.040	1.001	302	90	190	10.2	10.2
2	0.040	0.999	290	82	182	9.9	9.9
3	0.004	1.001	301	89	189	9.7	9.7
4	0.039	1.003	290	91	186	10.0	9.8
5	0.040	1.003	290	82	182	9.2	9.2
6	0.038	1.002	297	06	196	10.6	10.1
7	0.038	1.003	285	98	188	10.5	10.0
8	0.039	1.000	286	89	184	10.1	9.8
9	0.039	0.999	288	90	186	10.2	9.9
10	0.039	1.000	281	86	181	10.2	9.9
mean	0.039			190.3	186.3	10.06	9.85
std. dev.	0.001			7.3	4.5	0.40	0.27
Stnpped side in compression							
11	0.039	0.998	272	180	176	9.9	9.7
12	0.039	1.000	283	187	182	9.8	9.6
13	0.040	1.003	280	175	175	9.2	9.2
14	0.040	1.000	274	172	172	9.1	9.1
15	0.040	1.000	273	171	171	9.4	9.4
16	o.O39	0.997	272	180	176	10.0	9.8
17	0.040	1.001	278	174	174	9.5	9.5
18	0.039	1.002	283	187	182	10.0	9.8
19	0.040	1.000	290	182	182	9.7	9.7

20	0.041	1.001	286	171	175	9.2	9.4
mean	0.040			178.0	176.6	9.S8	9.50
std. dev.	0.001			6.1	4.1	0.35	0.23

TABLE 24.
Four-point Flexure Test Summary for fiberliass Samples.
('Ihe detailed results are given in table 25)

			Stress		Modulus	
Coating	Number	Orientation	Mean	Std. Dev.	Mean	Std. Dev
None	12	Tension	121.9	7.5	4.81	0.40
		Compression	122.5	9.4	4.34	0.26
Polyurethane	B49	Tension	118.5	4.6	3.74	0.20
		Compression	114.8	5.3	4.32	0.15

TABLE 25.

Four-point Flexure Test Results for Unpainted Fiberglass.
Fiberglass-epoxy; Control Sample 12; Support span = 0.72 u~ch.

				Stress		Modulus
	Thickness	Width	Load	Actual	Normalized	Actual
Specimen	(inch)	(inch)	(LB)	(ksi)	(ksi)	(msi)
side in tension						
1	0.035	1.004	300	132	128	5.6
2	0.037	1.006	288	113	116	4.4
3	0.036	1.007	294	122	121	4.9
4	0.036	1.006	295	122	122	4.5
5	0.037	1.006	290	113	116	4.4
6	0.037	1.006	296	116	119	4.5
7	0.035	1.006	306	134	130	5.2
8	0.036	1.007	292	121	120	4.8
9	0.035	1.054	308	129	125	5.1
10	0.037	0.955	284	117	120	4.7
mean	0.036			121.9	121.7	4.81
std dev.	0.001			7.5	4.5	0.40
side in compression						
11	0.037	1.008	280	110	113	4.2
12	0.036	1.006	278	115	116	4.6
13	0.037	1.009	292	114	118	3.9
14	0.035	1.009	285	125	122	4.3
15	0.034	1.007	275	128	121	4.6
16	0.037	1.008	286	113	116	4,4
17	0.034	1.008	290	134	128	4.5
18	0.034	0.956	281	137	130	4.7
19	0.037	1.054	336	126	130	4.1
20	0.037	0.957	300	124	128	4.1
mean	0.036			122.5	122.2	4.34
std. dev.	0.001			9.4	6.3	0.3

Fiberglass-epoxy w/Koriflex, Polyurethane; Sample B49; Support span = 0.72 inch.
Stripped side in tension

1	0.037	1.000	274	108		3.8
2	0.037	0.997	290	115		4.2
3	0.037	1.000	312	123		3.8
4	0.038	0.997	316	119		3.5
5	0.037	0.998	306	121		3.5
6	0.037	1.003	296	116		3.7
7	0.037	1.001	308	121		3.8
8	0.037	0.999	307	121		3.7
9	0.037	1.001	298	117		3.7
10	0.037	0.999	312	123		3.7
Mean	0.037			118.5		3.74
std. dev.	0.000			4.6		0.20

TABLE 25. (Continued)

				Stress		Modulus
	Thickness	Width	Load	Actual	Normalized	Actual
Specimen	(inch)	(inch)	(LB)	(ksi)	(ksi)	(msi)
Strippep side in compression						
11	0.037	0.999	289	114		4.3
12	0.037	0.999	300	118		4.5
13	0.037	0.999	316	125		4.5
14	0.038	0.999	292	109		4.1
15	0.037	0.999	291	115		4.4
16	0.038	0.998	192	109		4.2
17	0.038	0.999	290	109		4.1
18	0.037	1.000	288	114		4.3
19	0.037	0.999	307	121		4.5
20	0.037	1.000	289	114		4.3
mean	0.037			114.8		4.32
std dev.	0.000			5.3		0.15

TABLE 26.

Four-point Flexure Testing of Fiberglass.

(Performed by Anamet Laboratories, lnc)

Test with painted side in

		Dimension of			Flexural	Modulus of
Specimen		Specimen (inch)		Load	Strength	Elasticity
I.D.	Orientation	Width	Thickness	(LB)	(psi)	(psi)

A1	tension	1.005	0.039	269	95000	3.2×10^6
A2	compression	1.003	0.039	303	107000	3.1×10^6
A3	tension	1.003	0.039	255	90300	3.2×10^6
A4	compression	1.005	0.039	306	108000	3.0×10^6
A5	tension	1.002	0.036	254	100000	3.3×10^6
A6	compression	1.002	0.036	286	119000	3.3×10^6
Bl	tension	1.007	0.038	283	105000	3A x 10^6
B2	compression	1.006	0.038	300	112000	3A x 10^6
B3	tension	1.005	0.038	263	97900	3Ax 10^6
B4	compression	1.007	0.038	304	113000	3.2×10^6
B5	tension	1.003	0.037	264	104000	3.7×10^6
B6	compression	1.005	0.036	299	124000	3.4×10^6
Cl	tension	1.004	0.039	276	97600	3.2×10^6
C2	compression	1.004	0.039	289	102000	3.0×10^6
C3	mnsion	1.004	0.038	268	99800	3.3×10^6
C4	compression	1.004	0.038	299	111000	3.2×10^6
C5	tension	1.007	0.038	252	93600	3.4×10^6
C6	compression	1.005	0.037	290	114000	3.2×10^6
D1	tension	1.002	0.038	272	102000	3.5×10^6
D2	compression	1.001	0.039	314	111000	3.0×10^6
D3	Tension	1.002	0.038	263	98200	3.4×10^6
D4	compression	1.002	0.038	321	120000	3.3×10^6
D5	tension	1.003	0.038	262	97700	3.3×10^6
D6	compression	1.002	0.036	300	125000	3.5×10^6
E1	tension	1.003	0.039	282	99800	3.2×10^6
E2	compression	1.002	0.038	321	120000	3.3×10^6
E3	tension	1.002	0.038	267	99600	3.5×10^6
E4	compression	1.002	0.038	317	118000	3.3×10^6
E5	tension	i.oo2	0.037	278	109000	3.6×10^6
E6	compression	1.005	0.036	318	120000	3.5×10^6
X1	tension	1.005	0.038	247	91900	3.3×10^6
X2	compression	1.003	0.037	295	116000	3.3×10^6
X3	tension	1.005	0.037	245	%200	3.4×10^6
X4	compression	1.003	0.037	286	112000	3.2×10^6
X5	tension	1.003	0.036	245	102000	3.6×10^6
X6	comp~ession	1.003	0.036	279	116000	3.3×10^6

*Testing was performed LAW ASTM D 790-90, Test Method II - - four point loading. The following test parametas wae in effect crosshead rate - 0.02 in~min, load span - 0.36", and support span - 0.72".

APPENDIX III

POINTS OF CONTACT

JOINT PAINT REMOVAL STUDY
POINTS OF CONTACT

JOINT TECHNOLOGY EXCHANGE GROUP PRINCIPALS

CHAIRMAN: JOINT DEPOT MAINTENANCE ANALYSIS GROUP, JDMAG/MA, BLDG 280, DOOR 24, 4170, HEBBLE CREEK ROAD, WRIGHT-PATTERSON AFB OH 45433-5653, PHONE (937) 656-2762

MR TALMON PERKINS, JDMAG/MAT, BLDG 280, DOOR 24, 4170 HEBBLE CREEK ROAD, WRIGHT-PATTERSON AFB OH 45433-5653, PHONE (937) 656-2758

MR MIKE MCM1LLAN, HQ AFMC/ENB, 4375 CHIDLAW ROAD SUITE 6, WRIGHT-PATTERSON AFB OH 45433-5001, PHONE (937) 257-6484

MS CYNTHIA WHITE, NAVAL SEA SYSTEMS COMMAND, SEA-07223, 2211 JEFFERSON DAVIS HWY, ARLINGTON VA 22242-S160, PHONE (703) 602-3791, EX 162

MR RON VARGO, MARINE CORPS LOGISTICS BASE, 814 RADFORD BLVD, ALBANY GA 31704 1126, PHONE (912) 439-6805

. MR CHARLES OSECKI, SYSTEMS LIFE CYCLE READINESS OFFICE, AMSTAPBR, PICATINNY ARSENAL NJ 07806-5000, PHONE (201) 724-4067

LEAD SERVICE REPRESENTATIVES

PLASTIC MEDIA BLASTING

MR DAVE FREDERICK, OGDEN AIR LOGISTICS CENTER, OO-ALC/TIELM, 5851 F AVE, HILL AFB UT 84056-5713, PHONE (801) 775-2992

MR JAMES WHITFIELD, NAVAL AVIATION DEPOT, CODE 34520, MARINE CORPS AIR STATION, CHERRY POINT NC 28533-5030, PHONE (919) 466-7342

MR DARREN LUTOVSKY, PUGET SOUND NAVAL SHIPYARD, CODE 248.315, BREMERTON WA 98314-5000, PHONE (206) 476-6053

, (WHEAT STARCH BLASTING)

MR EDWARD COOPER, CORPUS CHRISTI ARMY DEPOT, SIOCC-ES-IE, MAIL STOP 35, 308 CRECY STREET, CORPUS CHRISTI TX 78419-5260, PHONE (512) 939-2214

<u>LASER</u>

MR DARREL TENNEY JR, NAVAL AVIATION DEPOT, CODE 93810, NAVAL AIR STATION, NORFOLK VA 23511-5899, PHONE (804) 441 3550

MR JIM HOLIDAY, CORPUS CHRI;STI ARMY DEPOT, SIOCC-ES-EI MAIL STOP 35, 308 CRECY STREET, CORPUS CHRISTI TX 78419-5260, PHONE (512) 939-2214

MR DAVE KERANEN, OGDEN AIR LOGISTICS CENTER, OO-ALC/TI HILL AFB UT 84056-5713, PHONE (919) 777-2042

<u>SODIUM BICARBONATE</u>

MR MIKE HAAS, SAN ANTONIO AIR LOGISTICS CENTER, SA-ALC/LAPSD, 485 QUENTIN ROOSEVELT RD, KELLY AFB TX 78241-5312, PHONE (512) 925-8541

MR WARREN AKERS, MARINE CORPS LOGISTICS BASE, 814 RADPORD BLVD, ALBANY GA 31704-1126, PHONE (912) 439-5317

<u>CARBON DIOXIDE PELLET BLASTING</u>

MR DON SVEJKOVSKY, OKLAHOMA CITY AIR LOGISTICS CENTER, OC-ALC/TEST, 4750 STAFF DR, TINKER AFB OK 73145-3317, PHONE (405) 736-5008

MR BILL CAIN, OKLAHOMA CITY AIR LOGISTICS CENTER, OC-ALC/LAPEP, 3001 STAFF DR STE 2Y56, TINKER AFB OK 73145-3025, PHONE (405) 736-5986

MS KATHLEEN MOONEY, NORFOLK NAVAL SHIPYARD, CODE 348.34, PORTSMOUTH VA 23709-5000, PHONE (202) 746-1487

<u>HIGH PRESSURE WATER</u>

MS JEANNIE WARNOCK, SACRAMENTO AIR LOGISTICS CENTER, SM-ALC/LARE, 3028 PEACEKEEPER WAY STE 2, MCCLELLAN AFB CA 95652-1018, PHONE (916) 643-2892

MR DON SVEJKOVSKY, OKLAHOMA CITY AIR LOGISTICS CENTER, OC-ALC/TIEST, 4750 STAFF DR, TINKER AFB OK 73145-300317, PHONE (405)736-5008